DETECTION OF NINE M8.0-L0.5 BINARIES: THE VERY LOW MASS BINARY POPULATION AND ITS IMPLICATIONS FOR BROWN DWARF AND VLM STAR FORMATION

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ABSTRACT

Use of the highly sensitive Hokupa'a/Gemini curvature wavefront sensor has allowed direct adaptive optics (AO) guiding on very low mass (VLM) stars with SpT=M8.0-L0.5. A survey of 39 such objects detected 9 VLM binaries (7 of which were discovered for the first time to be binaries). Most of these systems are tight (separation < 5 AU) and have similar masses ($\Delta Ks < 0.8$ mag; $0.85 < q < 1.0$). However, 2 systems (LHS 2397a and 2M2331016-040618) have large $\Delta Ks > 2.4$ mag and consist of a VLM star orbited by a much cooler L7-L8 brown dwarf companion. Based on this flux limited ($Ks < 12$ mag) survey of 39 M8.0-L0.5 stars (mainly from the 2MASS sample of Gizis et al. (2000)) we find a sensitivity corrected binary fraction in the range $15 \pm 7\%$ for M8.0-L0.5 stars with separations > 2.6 AU. This is slightly less than the $32 \pm 9\%$ measured for more massive M0-M4 dwarfs over the same separation range (Fischer & Marcy 1992). It appears M8.0-L0.5 binaries (as well as L and T dwarf binaries) have a much smaller semi-major axis distribution peak (~ 4 AU) compared to more massive M and G dwarfs which have a broad peak at larger ~ 30 AU separations. We also find no VLM binary systems (defined here as systems with $M_{tot} < 0.185 M_{\odot}$) with separations > 15 AU.

We briefly explore possible reasons why VLM binaries are slightly less common, nearly equal mass, and much more tightly bound compared to more massive binaries. We investigate the hypothesis that the lack of wide ($a > 20$ AU) VLM/brown dwarf binaries may be explained if the binary components were given a significant differential velocity kick. Such a velocity kick is predicted by current "ejection" theories, where brown dwarfs are formed because they are ejected from their embryonic mini-cluster and therefore starved of accretion material. We find that a kick from a close triple or quadruple encounter (imparting a differential kick of ~ 3 km/s between the members of an escaping binary) could reproduce the observed cut-off in the semi-major axis distribution at ~ 20 AU. However, the estimated binarity ($\lesssim 5\%$; Bate et al. (2002)) produced by such ejection scenarios is below the $15 \pm 7\%$ observed. Similarly, VLM binaries could be the final hardened binaries produced when a mini-cluster decays. However, the models of Sterzik & Durisen (1998); Durisen, Sterzik, & Pickett (2001) also cannot produce a VLM binary fraction above $\sim 5\%$. The observed VLM binary frequency could possibly be produced by cloud core fragmentation. Although, our estimate of a fragmentation-produced VLM binary semi-major axis distribution contains a significant fraction of "wide" VLM binaries with $a > 20$ AU in contrast to observation. In summary, more detailed theoretical work will be needed to explain these interesting results which show VLM binaries to be a significantly different population from more massive M & G dwarf binaries.

Subject headings: instrumentation: adaptive optics — binaries: general — stars: evolution — stars: formation — stars: low-mass, brown dwarfs

1. INTRODUCTION

Since the discovery of Gl 229B by Nakajima et al. (1995) there has been intense interest in the direct detection of brown dwarfs and very low mass (VLM) stars and their companions. According to the current models of Burrows et al. (2000) and Chabrier et al. (2000), stars with spectral types of M8.0-L0.5 will be just above the stellar/substellar boundary. However, modestly fainter companions to such primaries could themselves be substellar. Therefore, a survey of M8.0-L0.5 stars should detect binary systems consisting of VLM primaries with VLM or brown dwarf secondaries.

The binary frequency of M8.0-L0.5 stars is interesting in its own right since little is known about how common M8.0-L0.5 binary systems are. It is not clear currently if the M8.0-L0.5 binary separation distribution is similar to that of M0-M4 stars; in fact, there is emerging evidence that very low mass L & T dwarf binaries tend to have smaller separations and possibly lower binary frequencies compared to more massive M and G stars (Martín, Brandner, & Basri 1999; Reid et al. 2001a; Burgasser et al. 2003).

Despite the strong interest in such very low mass (VLM) binaries ($M_{tot} < 0.185 M_{\odot}$), only 24 such systems are known (see Table 4 for a complete list). A brief overview of these systems starts with the first double L dwarf system which was imaged by HST/NICMOS by Martín, Brandner, & Basri (1999). A young spectroscopic binary brown dwarf (PPL 15) was detected in the Pleiades (Basri & Martín (1999)) but this spectroscopic system is too tight to get separate luminosities for each component. A large HST/NICMOS imaging survey by Martín et al. (2000) of VLM dwarfs in the Pleiades failed to detect any brown dwarf binaries with separations $> 0.2''$ ($\gtrsim 27$ AU). Detections of nearby field binary systems were more successful. The nearby object Gl 569B was resolved into a $0.1''$ (1 AU) binary brown dwarf at Keck and the 6.5m MMT (Martín et al. (1999); Kenworthy et al. (2001); Lane et al. (2001)). Keck seeing-limited NIR imaging marginally resolved two more binary L stars (Koerner et al. (1999)). A survey with WFPC2 detected four more (three newly discovered and one confirmed from Koerner et al. (1999)) tight equal magnitude binaries out of a sample of 20 L dwarfs (Reid et al. (2001a)). From the same survey Reid et al. (2002) found a M8 binary (2M1047; later discovered independently by our survey). Guiding on HD130948 with adaptive optics (AO), Potter et al. (2002a) discovered a companion binary brown dwarf system. Recently, Burgasser et al. (2003) have detected two T dwarf binaries with HST. Finally, 12 more L dwarf binaries have been found by analyzing all the currently remaining HST/WFPC2 data collected on L dwarfs (Bouy et al. 2003). Hence, the total number of binary VLM stars and brown dwarfs currently known is just 24. Of these, all but one have luminosities known for each component, since one is a spectroscopic binary.

Here we have carried out our own high-spatial resolution binary survey of VLM stars employing adaptive optics. In total, we have detected 12 VLM binaries (10 of these are new discoveries) in our AO survey of 69 VLM stars. Three of these systems (LP415-20, LP475-855, & 2MASSW J1750129+442404) have M7.0-M7.5 spectral types and are discussed in detail elsewhere (Siegler et al. 2003). In this paper, we discuss the remaining 9 cooler binaries with M8.0-L0.5 primaries detected in our survey (referred herein as M8.0-L0.5 binaries even though they may contain L1-L7.5 companions; see Table 2 for a complete list of these systems).

Two of these systems (2MASSW J0746425+200032 and 2MASSW J1047127+402644) were in our sample but were previously imaged in the visible by HST and found to be binaries (Reid et al. (2001a, 2002)). Here we present the first resolved IR observations of these two systems and new astrometry. The seven remaining systems were all discovered to be binaries during this survey. The first four systems discovered in our survey (2MASSW J1426316+155701, 2MASSW J2140293+162518, 2MASSW J2206228-204705, and 2MASSW J2331016-040618) have brief descriptions in Close et al. (2002b). However, we have re-analyzed the data from Close et al. (2002b) and include it here for completeness with slightly revised mass estimates. The very interesting M8/L7.5 system LHS 2397a discovered during this survey is discussed in detail elsewhere (Freed, Close, & Siegler 2003) yet is included here for completeness. The newly discovered binaries 2MASSW J1127534+741107 and 2MASSW J1311391+803222 are presented here for the first time.

These nine M8.0-L0.5 binaries are a significant addition to the other very low mass M8-T6 binaries known to date listed in Table 4 (Basri & Martín 1999; Martín, Brandner, & Basri 1999; Koerner et al. 1999; Reid et al. 2001a; Lane et al. 2001; Potter et al. 2002a; Burgasser et al. 2003; Bouy et al. 2003). With relatively short periods our new systems will likely play a significant role in the mass-age-luminosity calibration for VLM stars and brown dwarfs. It is also noteworthy that we can start to characterize this new population of M8.0-L0.5 binaries. We will outline how VLM binaries are different from their more massive M and G counterparts. Since VLM binaries are so tightly bound we hypothesize that very little dynamical evolution of the distribution has occurred since their formation. We attempt to constrain the formation mechanism of VLM stars and brown dwarfs from our observed semi-major axis distribution and binarity statistics.

2. AN AO SURVEY OF NEARBY M8.0-L0.5 FIELD STARS

As outlined in detail in Close et al. (2002a), we utilized the University of Hawaii curvature adaptive optics system Hokupa'a (Graves et al. 1998; Close et al. 1998), which was a visitor AO instrument on the Gemini North Telescope. This highly sensitive curvature AO system is well suited to locking onto nearby, faint ($V \sim 20$), red ($V - I > 3$), M8.0-L0.5 stars to produce $\sim 0.1''$ images (which are close to the $0.07''$ diffraction-limit in the K' band). We can guide on such faint ($I \sim 17$) targets with a curvature AO system (such as Hokupa'a) by utilizing its zero-read noise wavefront sensor (for a detailed explanation of how this is possible see Siegler, Close, & Freed (2002)). We utilized this unique capability to survey the nearest extreme M and L stars (M8.0-L0.5) to characterize the nearby VLM binary population.

Here we report the results of all our Gemini observing runs in 2001 and 2002. We have observed all 32 M8.0-M9.5 stars with $Ks < 12$ mag from the list of Gizis et al. (2000). It should be noted that the M8.0-M9.5 list of Gizis et al. (2000) has some selection constraints: galactic latitudes are all > 20 degrees; and from $0 < RA < 4.5$ hours $DEC < 30$ degrees; and there are gaps in the coverage due to the past availability of the 2MASS scans. A bright L0.5 dwarf with $Ks < 12$ was also observed (selected from Kirkpatrick et al. (2000)). Six additional bright ($Ks < 12$) M8.0-M9.5 stars were selected from Reid et al. (2002) and Cruz et al. (2003). In total 39 M8.0-L0.5 stars have now been imaged at high resolution ($\sim 0.1''$) with AO compensation in our survey. For a complete list of these M8-L0.5 target stars see Table 1 (single stars) and Table 2 (stars found to be binaries).

Nine of our 39 targets were clearly tight binaries ($sep < 0.5''$). We observed each of these objects by dithering over 4 different positions on the QUIRC 1024×1024 NIR ($1 - 2.5\mu m$) detector (Hodapp et al. 1996) which has a $0.0199''$/pixel plate scale at Gemini North. At each position we took 3x10s exposures at J, H, K', and 3x60s exposures at H, resulting in unsaturated 120s exposures at J, H, and K' with a deep 720s exposure at H band for each binary system.

3. REDUCTIONS

We have developed an AO data reduction pipeline in the IRAF language which maximizes sensitivity and image resolution. This pipeline is standard IR AO data reduction and is described in detail in Close et al. (2002a).

Unlike conventional NIR observing at an alt-az telescope (like Gemini), we disable the Cassegrain rotator so that the pupil image is fixed w.r.t. the detector. Hence the optics are not rotating w.r.t. the camera or detector. In this manner the residual static PSF aberrations are fixed in the AO images enabling quick identification of real companions as compared to PSF artifacts. The pipeline cross-correlates and aligns each image, then rotates each image so north is up and east is to the left, then median combines the data with an average sigma clip rejection at the $\pm 2.5\sigma$ level. By use of a cubic-spline interpolator the script preserves image resolution to the < 0.02 pixel level. Next the custom IRAF script produces two final output images, one that combines all the images taken and another where only the sharpest 50% of the images are combined.

This pipeline produced final unsaturated 120s exposures at J ($FWHM \sim 0.15''$) , H ($FWHM \sim 0.14''$), and K' ($FWHM \sim 0.13''$) with a deep 720s exposure ($FWHM \sim 0.14''$) at H band for each binary system. The dithering produces a final image of 30x30$''$ with the most sensitive region ($10 \times 10''$) centered on the binary. Figures 1 and 2 illustrates K' images of each of the systems.

In Table 2 we present the analysis of the images taken of the 9 new binaries from our Gemini observing runs. The photometry was based on DAOPHOT PSF fitting photometry (Stetson 1987). The PSFs used were the reduced 12x10s unsaturated data from the next (and previous) single VLM stars observed after (and before) each binary. The PSF stars always had a similar IR brightness, a late M spectral type, and were observed at a similar airmass. The resulting $\Delta magnitudes$ between the components are listed in Table 2; their errors in Δmag are the differences in the photometry between two similar PSF stars. The individual fluxes were calculated from the flux ratio measured by DAOPHOT. We made the assumption $\Delta K' \sim \Delta Ks$, which is correct to 0.02 mag according the models of Chabrier et al. (2000). Assuming $\Delta K' = \Delta Ks$ allows us to use the 2MASS integrated Ks fluxes of the blended binaries to solve for the individual Ks fluxes of each component (see Table 3).

The platescale and orientation of QUIRC was determined from a short exposure of the Trapezium cluster in Orion and compared to published positions as in Simon, Close, & Beck (1999). From these observations a platescale of $0.0199 \pm 0.0002''$/pix and an orientation of the Y-axis (0.3 ± 0.3 degrees E of north) was determined. Astrometry for each binary was based on the PSF fitting. The astrometric errors were based on the range of the 3 values observed at J, H, and K' and the systematic errors in the calibration added in quadrature.

4. ANALYSIS

4.1. *Are the companions physically related to primaries?*

Since Gizis et al. (2000) only selected objects > 20 degrees above the galactic plane, we do not expect many background late M or L stars in our images. In the 3.6x10^4 square arcsecs already surveyed, we have not detected a very red $J - Ks > 0.8$ mag background object in any of the fields. Therefore, we estimate the probability of a chance projection of such a red object within $< 0.5''$ of the primary to be $<$ 2x10^{-5}. Moreover, given the rather low space density ($0.0057 \pm 0.0025 pc^{-3}$) of L dwarfs (Gizis et al. 2001), the probability of a background L dwarf within $< 0.5''$ of any of our targets is $< 10^{-16}$. We conclude that all these very red, cool objects are physically related to their primaries.

4.2. *What are the distances to the binaries?*

Unfortunately, there are no published trigonometric parallaxes for six of the nine systems. The three systems with parallaxes are: 2M0746 (Dahn et al. 2002); LHS 2397a (van Altena, Lee, & Hoffleit 1995); and 2M2331 (associated with a Hipparcos star HD221356 Gizis et al. (2000)). For the remaining six systems without parallaxes we can estimate the distance based on the trigonometric parallaxes of other well studied M8.0-L0.5 stars from Dahn et al. (2002). The distances of all the primaries were determined from the absolute Ks magnitudes (using available 2MASS photometry for each star with trigonometric parallaxes from Dahn et al. (2002)), which can be estimated by $M_{Ks} = 7.71 + 2.14(J - Ks)$ for M8.0-L0.5 stars (Siegler et al. 2003). This relationship has a 1σ error of 0.33 mag which has been added in quadrature to the J and Ks photometric errors to yield the primary component's M_{Ks} values in Table 3 and plotted as crosses in Figures 3 - 11. As can be seen from Table 3 all but one of our systems are within 29 pc (the exception is 2M1127 at ~ 33 pc).

4.3. *What are the spectral types of the components?*

We do not have spatially resolved spectra of both components in any of these systems; consequently we can only try to fit the M_{Ks} values in Table 3 to the relation $SpT = 3.97 M_{Ks} - 31.67$ which is derived from the dataset of Dahn et al. (2002) by Siegler et al. (2003). Unfortunately, the exact relationship between M_{Ks} and VLM/brown dwarf spectral types is still under study. It is important to note that these spectral types are only a guide since the conversion from M_{Ks} to spectral type carries at least ± 1.5 spectral subclasses of uncertainty. Fortunately, none of the following analysis is dependent on these spectral type estimates.

It is interesting to note that six of these secondaries are likely L dwarfs. In particular 2M2331B is likely a L7 and LHS 2397aB is likely a L7.5. Both 2M2331B and LHS 2397aB are very cool, late L companions.

4.4. *What are ages of the systems?*

Estimating the exact age for any of these systems is difficult since there are no Li measurements yet published (which could place an upper limit on the ages). An exception to this is LHS 2397a for which no Li was detected Martín, Rebolo, & Magazzu (1994). For a detailed discussion on the age of LHS 2397a see Freed, Close, & Siegler (2003). For each of the remaining systems we have conservatively assumed that the whole range of common ages in the solar neighborhood (0.6 to 7.5 Gyr) may apply to each system (Caloi et al. 1999). However, Gizis et al. (2000) observed very low proper motion ($V_{tan} < 10$ km/s) for the 2M1127, 2M2140, and 2M2206 systems. These three systems are among the lowest velocity M8's in the entire survey of Gizis et al. (2000) suggesting a somewhat younger age since these systems have not yet developed a significant random velocity like the other older (~ 5 Gyr) M8.0-L0.5 stars in the survey. Therefore, we assign a slightly younger age of $3.0^{+4.5}_{-2.4}$ Gyr to these 3 systems, but leave large error bars allowing ages from 0.6-7.5 Gyr (~ 3 Gyr is the maximum age for the kinematically young stars found by Caloi et al. (1999)). The other binary systems 2M0746, 2M1047, 2M1311, and 2M2331 appear to have normal V_{tan} and are more likely to be older systems. Hence we assign an age of $5.0^{+2.5}_{-4.4}$ Gyr to these older systems (Caloi et al. 1999). It should be noted that there is little significant difference between the evolutionary tracks for ages $1 - 10$

Gyr when $SpT < L0$ (Chabrier et al. 2000). Therefore, the exact age is not absolutely critical to estimating the approximate masses for M8.0-L0.5 stars (see Figure 3).

4.5. *The masses of the components*

To estimate masses for these objects we will need to rely on theoretical evolutionary tracks for VLM stars and brown dwarfs. Calibrated theoretical evolutionary tracks are required for objects in the temperature range 1400-2600 K. Recently such a calibration has been performed by two groups using dynamical measurements of the M8.5 Gl569B brown dwarf binary. From the dynamical mass measurements of the Gl569B binary brown dwarf (Kenworthy et al. 2001; Lane et al. 2001) it was found that the Chabrier et al. (2000) and Burrows et al. (2000) evolutionary models were in reasonably good agreement with observation. In Figures 3 to 11 we plot the latest DUSTY models from Chabrier et al. (2000) which have been specially integrated across the Ks filter so as to allow a direct comparison to the 2MASS Ks photometry (this avoids the additional error of converting from Ks to K for very red objects). We extrapolated the isochrones from 0.10 to 0.11 $M_{\odot}$ to cover the extreme upper limits of some of the primary masses in the figures.

We estimate the masses of the components based on the age range of 0.6-7.5 Gyr and the range of M_{Ks} values. The maximum mass relates to the minimum M_{Ks} and the maximum age of 7.5 Gyr. The minimum mass relates to the maximum M_{Ks} and the minimum age of 0.6 Gyr. These masses are listed in Table 3 and illustrated in Figures 3 to 11 as filled polygons.

At the younger ages ($< 1 Gyr$), the primaries may be on the stellar/substellar boundary, but they are most likely VLM stars. The substellar nature of the companion is very likely in the case of 2M2331B and LHS 2397aB, possible in the cases of 2M0746B, 2M1426B, and 2M2140B, and unlikely in the cases of 2M1047B, 2M1127B, 2M1311B, and 2M2206B which all appear to be VLM stars like their primaries. Hence two of the companions are brown dwarfs, three others may also be substellar, and four are likely VLM stars.

5. DISCUSSION

5.1. *The binary frequency of M8.0-L0.5 stars*

We have carried out the largest flux limited ($Ks < 12$) high spatial resolution survey of M8.0-L0.5 primaries. Around these 39 M8.0-L0.5 targets we have detected 9 systems that have companions. Since our survey is flux limited we need to correct for our bias toward detecting equal magnitude binaries that "leak" into our sample from further distances. For example, an equal magnitude M8 binary could have an integrated 2MASS magnitude of Ks=12 mag but be actually located at 36 pc whereas a single M8 star of Ks=12 would be located just 26 pc distant. Hence our selection of $Ks < 12$ leads to incompleteness of single stars and low mass ratio ($q \equiv M_2/M_1$) binaries past $D \sim 26$ pc. More exactly, 88% of our binary systems are within 29.1 pc (distances calculated using only the *primary's* apparent magnitude) and 88% of our single stars are within 23.4 pc. Therefore, we are probing $\sim (29.1/23.4)^3 = 1.92$ times more volume with the brighter (combined light) of the binaries compared to the single (hence fainter) M8.0-L0.5 stars. Hence, the corrected binary frequency is $9/39/1.92 = 12 \pm 4\%$ (where the error is only Poisson error).

There is another selection effect due to the instrumental PSF which prevents detection of very faint companions very close to the primaries. At the smallest separations of $0.1 - 0.2''$ we are only sensitive to relatively bright companions of $\Delta K' \lesssim 1 mag$. Much fainter companions ($\Delta K' \sim 5 mag$) can be detected at slightly wider ($\sim 0.25''$) separations, and very low mass companions ($\Delta H \sim 10 mag$) could be detected at $\sim 1''$ separations in our deep 720s H images. Therefore, we are likely insensitive to faint ($\Delta K' > 1.0$) companions in the separation range of $0.1 - 0.2''$. However, if we assume that the mass ratio (q) distribution for M8.0-L0.5 stars is close to flat (as it is for M0-M4 binaries; Fischer & Marcy (1992)), then we would expect at least as many binaries with $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag. Although we do not have enough data currently to definitely derive the q distribution for M8.0-L0.5 binaries, we can note that for the four systems with separations $> 0.2''$ we observed an equal number of $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag systems. So it appears reasonable that there should also be an equal number of $\Delta K' > 1.0$ as $\Delta K' < 1.0$ mag systems in the range $0.1 - 0.2''$. Consequently, based on our detection of five systems with $\Delta K' < 1$ mag with separations of $0.1 - 0.2''$ we would expect to have ~ 5 systems with $\Delta K' > 1.0$ in the range $0.1 - 0.2''$. In reality we detected no systems with $\Delta K' > 1.0$ with separations $0.1 - 0.2''$. Therefore, to correct for instrumental insensitivity we need to increase the number of binary systems by 5 in the range $0.1 - 0.2''$. Based on this assumption about the mass ratio distribution there should be ~ 10 binaries from $0.1 - 0.2''$ when correcting for our instrumental insensitivity. Therefore, the total count for all separations $> 0.1''$ should be 14 ± 4 systems assuming a Poisson error. Therefore, the corrected M8.0-L0.5 binary frequency would be $14/39/1.92 = 19 \pm 7\%$ for separations $> 0.10''$ or $\gtrsim 2.6$ AU. Hence we have a range of possible volume-limited binary frequencies (BF) from 12% ($q \sim 1$) up to 19% (where q is assumed to be flat necessitating a large correction for insensitivity).

As a check we can re-derive these values of the true volume-limited BF in a manner after Burgasser et al. (2003) for the two limiting cases of $q = 1$ up to a flat q distribution. We can write,

$$BF = -BF^{obs}/(BF^{obs} + \alpha(BF^{obs} - 1)) \quad (1)$$

where BF^{obs} is the observed uncorrected binarity ($BF^{obs} = 9/39 = 23\%$), and where α is the fractional increase in volume sampled for binaries with a flux ratio $\rho = F_B/F_A$ and a flux ratio distribution $f(\rho)$. As in (Burgasser et al. 2003) we can calculate α by,

$$\alpha \equiv \frac{\int_0^1 (1+\rho)^{3/2} f(\rho) d\rho}{\int_0^1 f(\rho) d\rho} \quad (2)$$

We consider two limiting cases for the $f(\rho)$ distribution: 1) if all the systems are equal magnitude ($q = \rho = 1$) then $\alpha = 2^{(3/2)} = 2.8$ and the BF=12%; 2) if there is a flat $f(\rho)$ distribution then $\alpha = 1.9$ and the BF=19%. Consequently, the binary frequency range is 12-19% which is identical to the range estimated above. Later we will see (Figure 14) the true $f(\rho)$ is indeed a compromise between flat and unity; hence we split the difference and adopt a binary frequency of $15 \pm 7\%$ where the error is the Poisson error (5%) added in quadrature to the ($\sim 4\%$) uncertainty due to the possible range of the q distribution ($1.9 < \alpha < 2.8$). *It appears that for systems with separations* $2.6 < a < 300$ *AU the M8.0-L0.5 binary frequency is within the range* $15 \pm 7\%$.

Our M8.0-L0.5 binary fraction range of $15 \pm 7\%$ is marginally consistent with the $28 \pm 9\%$ measured for more massive M0-M4 dwarfs (Fischer & Marcy 1992) over the same separation/period range ($2.6 < a < 300$ AU) probed in this study. However, Fischer & Marcy (1992) found a binary fraction of 32±9% over the whole range of $a > 2.6AU$. If we assume that there are *no* missing low mass wide binary systems with $a > 300$ AU (this is a good assumption since such wide *sep* $\gtrsim 15''$ systems would have been easily detected in the 2MASS point source catalog as is illustrated in Figure 12), then our binary fraction of $15 \pm 7\%$ would be valid for all $a > 2.6$ AU and would therefore be slightly lower than $32 \pm 9\%$ observed for M0-M4 dwarfs with $a > 2.6$ AU by Fischer & Marcy (1992). Hence it appears VLM binaries ($M_{tot} < 0.185 M_{\odot}$) are less common (significant at the 95% level) than M0-M4 binaries over the whole range $a > 2.6$ AU.

5.2. *The separation distribution function for M8.0-L0.5 binaries*

The M8.0-L0.5 binaries are much tighter than M0-M4 dwarfs in the distribution of their semi-major axes. The M8.0-L0.5 binaries appear to peak at separations ~ 4 AU which is significantly tighter than the broad ~ 30 AU peak of both the G and M star binary distributions (Duquennoy & Mayor 1991; Fischer & Marcy 1992). This cannot be a selection effect since we are highly sensitive to all M8.0-L0.5 binaries with *sep* $> 20 - 300$ AU (even those with $\Delta H > 10$ mag). *Therefore, we conclude that M8.0-L0.5 stars likely have slightly lower binary fractions than G and early M dwarfs, but have significantly smaller semi-major axes on average.*

6. THE VLM BINARY POPULATION IN GENERAL

More observations of such systems will be required to see if these trends for M8.0-L0.5 binaries hold over bigger samples. It is interesting to note that in Reid et al. (2001a) an HST/WFPC2 survey of 20 L stars found 4 binaries and a similar binary frequency of 10-20%. The widest L dwarf binary in Koerner et al. (1999) had a separation of only 9.2 AU. A smaller HST survey of 10 T dwarfs by Burgasser et al. (2003) found two T binaries and a similar binary frequency of $9^{+15}_{-4}\%$ with no systems wider than 5.2 AU. Therefore, it appears all M8.0-L0.5, L, and T binaries may have similar binary frequencies $\sim 9 - 15\%$ (for $a > 3$ AU).

In Table 4 we list all the currently known VLM binaries (defined in this paper as $M_{tot} < 0.185 M_{\odot}$) from the high-resolution studies of Basri & Martín (1999); Martín, Brandner, & Basri (1999); Koerner et al. (1999); Reid et al. (2001a); Lane et al. (2001); Potter et al. (2002a); Burgasser et al. (2003); Bouy et al. (2003). As can be seen from Figure 13 VLM binaries have a ~ 4 AU peak in their separation distribution function with no systems wider than 15 AU.

From Figure 14 we see that most VLM binaries have nearly equal mass companions, and no system has $q < 0.7$. This VLM q distribution is different from the nearly flat q distribution of M0-M4 stars (Fischer & Marcy 1992). Since the HST surveys of Martín, Brandner, & Basri (1999); Reid et al. (2001a); Burgasser et al. (2003); Bouy et al. (2003) and our AO surveys were sensitive to $1.0 > q \gtrsim 0.5$ for systems with $a > 4$ AU, the dearth of systems with $0.8 > q > 0.5$ in Figure 14 is likely a real characteristic of VLM binaries and not just a selection effect of insensitivity. However, these surveys become insensitive to tight ($a < 4$ AU) systems with $q < 0.5$, hence the lack of detection of such systems may be purely due to insensitivity.

6.1. *Why are there no wide VLM binaries?*

It is curious that we were able to detect 8 systems in the range $0.1 - 0.25''$ but no systems were detected past $0.5''$ (~ 16 AU). This is surprising since we (as well as the HST surveys of Martín, Brandner, & Basri (1999); Reid et al. (2001a); Burgasser et al. (2003); Bouy et al. (2003)) are very sensitive to any binary system with separations $> 0.5''$ and yet none were found. One may worry that this is just a selection effect in our target list from the spectroscopic surveys of Gizis et al. (2000) and Cruz et al. (2003), since they only selected objects in the 2MASS *point source catalog*. There is a possibility that such a catalog would select against $0.5'' - 2.0''$ binaries if they appeared extended in the 2MASS images. However, we found that marginally extended PSFs due to unresolved binaries (separation $\lesssim 2''$) were not being classified as extended and therefore were not removed from the 2MASS point source catalog. For example, Figure 12 illustrates that no known T-Tauri binary from list of White & Ghez (2001) was removed from the 2MASS point source catalog. Although, due to the relatively poor resolution of 2MASS (FWHM $\sim 2 - 3''$), only systems with separations $> 3''$ were classified as binaries by 2MASS, all the other T-Tauri binaries were unresolved and mis-classified as single stars. In any case, we are satisfied that no "wide" ($0.5'' \lesssim$ separation $\lesssim 2''$) VLM candidate systems were tagged as extended and removed from the 2MASS point source catalog. Therefore, the lack of a detection of any system wider than $0.5''$ is not a selection effect of the initial use of the 2MASS point source catalog for targets.

Our observed dearth of wide systems is supported by the results of the HST surveys where out of 16 L and two T binaries, no system with a separation > 13 AU was detected. We find the widest M8.0-L0.5 binary is 16 AU while the widest L dwarf binary is 13 AU (Bouy et al. 2003), and the widest T dwarf binary is 5.2 AU (Burgasser et al. 2003). However, M dwarf binaries just slightly more massive ($\gtrsim 0.2 M_{\odot}$) in the field (Reid & Gizis 1997a) and in the Hyades (Reid & Gizis 1997b) have much larger separations from 50-200 AU.

In Figure 15 we plot the sum of primary and secondary component masses as a function of the binary separation for all currently known VLM binaries listed in Table 4. It appears that all VLM and brown dwarf binaries (open symbols) are much tighter than the slightly more massive M0-M4 binaries (solid symbols).

If we examine more massive (SpT=A0-M5) wide binary systems from Close et al. (1990), we see such wide binaries have maximum separations best fit by $a_{max} \sim 1000(M_{tot}/0.185M_\odot)$ AU in Figure 15. Any system with such a separation ($a = a_{max}$) will be disrupted by a differential velocity impulse (or "escape kick") to one component of $V_{esc} > 0.57$ km/s (see the solid upper line in Figure 15). However, if we try to fit the VLM/brown dwarf binaries (defined here as systems with $M_{tot} < 0.185M_\odot$) we find the maximum separation is better predicted by $a_{max_{VLM}} \sim 23.2(M_{tot}/0.185M_\odot)$ AU (lower dashed line in Figure 15). Since these are much smaller separations we find that any system with such a separation ($a = a_{max_{VLM}}$) will require a larger escape velocity kick of $V_{esc} > 3.8$ km/s to become unbound.

To try and glean if VLM/brown dwarf binaries are really more tightly bound, we compare their binding energy to that of more massive binaries. Figure 16 illustrates how the minimum binding energy of binaries with $M_{tot} < 0.185M_\odot$ is 16x harder than more massive field M-G binaries. In other words the widest binaries with $M_{tot} < 0.185M_\odot$ appear to be 16 times "more bound" than the widest binaries with $M_{tot} > 0.185M_\odot$.

This hardening could be a relic from dissipative star/disk interactions with the accretion disks around each star (McDonald & Clarke 1995) and/or it could be from an ejection event, dynamical decay, or fragmentation. We will briefly explore some of these possibilities in the next sections.

6.1.1. *Can ejection explain the lack of wide VLM binaries?*

Reipurth & Clarke (2001) suggest that VLM binary systems may have been ejected from their "mini-cluster" stellar nurseries in close triple or quadruple encounters with more massive objects early in their lives. Consequently, these ejected VLM objects are starved of accretion material and their growth is truncated (see a cartoon of this scenario in Fig. 17). Sterzik & Durisen (1998) estimate that around 5% of ejecta from pentuple systems are binaries. The typical ejection velocity estimated by Sterzik & Durisen (1998); Reipurth & Clarke (2001) is ~ 3 km/s for single objects (on average these ejected single objects have masses$> 0.185M_\odot$). Hence one might hypothesize tight VLM binaries of similar total mass may be ejected at similar velocities; however, we caution that more detailed simulations are required to estimate realistic ejection velocities. In any case, only tightly bound binaries will survive the ejection process. This may explain the additional tightness of the VLM/brown dwarf binaries in Figure 15. More loosely bound VLM binaries were dissolved ("kicked" past the $V_{esc} = 3.8$ km/s line in Fig.15) when they were ejected from their mini-cluster. Hence, only relatively hard $a < 16$ AU ($V_{esc} > 3.8$ km/s) low mass binaries have survived until today.

However, the ejection paradigm of Reipurth & Clarke (2001) as simulated in detail by Bate et al. (2002) only predict a VLM/brown dwarf binary fraction of $\lesssim 5\%$ which is below the $15 \pm 7\%$ observed for M8.0-L0.5 binaries and the 9^{+15}_{-4} observed for T dwarf binaries (Burgasser et al. 2003). Therefore, further simulations will be required to see if a larger ($\gtrsim 9\%$) binary frequency can be produced when low mass binaries are ejected from the mini-cluster.

6.1.2. *Is the dearth of wide low mass binaries due to Galactic dynamical evolution?*

Over the lifetime of a binary there will be many stochastic encounters, which will increase the potential energy (and therefore its separation) of the binary slowly over time. Eventually, these encounters may also disrupt the binary. In fact, this disruption timescale is roughly proportional to M_{tot}/a for separations < 200 AU according to the detailed models of Weinberg et al. (1987). As we can see from the solid line in Figure 15, a line of constant M_{tot}/a or constant V_{esc} (where $V_{esc} = 0.57$ km/s) can fit the widest A0-M0 binaries, but the same line cannot fit the widest of the much tighter VLM binaries (open symbols). This is quite puzzling since wide (> 200 AU) VLM binaries should get wider throughout their lifetime until they reach $a = a_{max} \sim 1000(M_{tot}/0.185M_\odot)$ AU. By this point, they have reached the average minimum binding energy ($-E_{bind_{min}} \sim 3\text{x}10^{41}$ erg) of field wide binaries and are likely to be disrupted by a differential kick of only 0.6 km/s.

So why do we not observe wider VLM binaries if they should dynamically evolve to $a = a_{max} \sim 1000(M_{tot}/0.185M_\odot)$AU $\sim$ 1000AU over time? It is critical to note that only binaries that are wider than $1000(M_{tot}/M_\odot)$ AU are wide enough to significantly evolve in the galactic disk according the detailed models of Weinberg et al. (1987). Therefore, only binaries of initial separation (a_o) greater than $a_o \sim 185$ AU for $M_{tot} = 0.185M_\odot$ will evolve to the minimum binding energy (which corresponds to separation of $a_{max} \sim 1000$ AU) over a 12 Gyr lifetime. Any systems formed tighter than $1000(M_{tot}/M_\odot)$ AU will not dynamically evolve to significantly wider separations over time.

So why don't we detect any 185-1000 AU VLM binaries? The answer may be very simple. If the formation process that forms VLM/brown dwarf binaries cannot produce binaries with $a_o > 1000(M_{tot}/M_\odot)$ AU then there will be no significant evolution of a during the lifetime of the binaries. In other words the observed a distribution will be similar to the initial distribution (a_o). Since we currently observe no VLM systems with $a > 100$ AU, the observed separation distribution for VLM binaries is likely the same as their initial distribution. Figures 15 and 16 suggest that a_o for VLM stars is strongly truncated at ~ 16 AU. In addition, the observed values of $V_{esc} > 3.8$ km/s and $-E_{bind} > 50 \times 10^{41}$ erg are therefore likely relics of the formation of these VLM binaries and need to be explained by any successful model of star/brown dwarf formation.

6.1.3. *Could VLM binaries be the decay product of a dissolving mini-cluster?*

In the dynamical decay of these "mini-clusters" it is likely that the most massive components become a hardened binary as the lower mass objects are ejected by triple encounters (see bottom of Figure 17). Reipurth & Clarke (2001) have hypothesized that VLM binaries may also be ejected from these mini-clusters since they have very low masses and are tight enough to remain bound after ejection. However, it is also possible that VLM binaries are not ejected but instead persevere until they are the final most tightly bound binary remaining after the "mini-cluster" decays.

The decay of 3,4, and 5-body "mini-clusters" has been studied by Sterzik & Durisen (1998). The final residual binaries produced by such decays have characteristics similar to those observed for VLM binaries. In particular, Sterzik & Durisen (1998) predict that binaries composed of stars with masses from $0.1 - 0.2 M_{\odot}$ would have separations of ~ 10 AU compared to ~ 30 AU for more massive stars. Furthermore, they predict the mass ratio q to be in the range 0.6-1.0. Moreover, they predict a fairly sharp cut-off at ~ 10 AU for "wide" low mass binaries. All these predictions are roughly consistent with our observations of the VLM binary population.

Since the final binary produced is typically biased towards the two or three most massive members of the mini-cluster (true of $\sim 99 - 98\%$ cluster decays; Sterzik & Durisen (1998)), the likelihood of the most massive objects in the mini-cluster both having masses less than $0.090 M_{\odot}$ is rather small. Indeed, the binary fraction of $0.2 < M_{tot} < 0.4 M_{\odot}$ binaries predicted by Sterzik & Durisen (1998) is very small ($\leq 1\%$) if each member of the cluster are picked randomly from the IMF. Even smaller binary fractions would be predicted for even lower mass VLM binaries ($M_{tot} < 0.185 M_{\odot}$). Therefore, only a fraction of our VLM binaries (observed to have a binary frequency of $\sim 9 - 15\%$) are likely the residual hardened binaries remaining after a mini-cluster dissolves.

Recently, Durisen, Sterzik, & Pickett (2001) have modeled a "two-step IMF" to produce a more realistic binary population from F to early M spectral types. As in Sterzik & Durisen (1998) the VLM binary characteristics predicted in general are similar to those observed. In particular, this is true for their models which include brown dwarfs in the IMF. However, they note that models which include brown dwarfs overestimate the number of G-dwarf binaries ($BF(1.0 M_{\odot}) \sim 75\%$). Moreover, while these models do predict some binary VLM systems ($BF(0.1 M_{\odot} \lesssim 5\%$) they still underestimate the frequency of such systems compared to the $15 \pm 7\%$ observed here for binaries in this mass range.

6.1.4. *Can we explain the truncation at ~ 16 AU simply by an initial semi-major axis distribution produced by fragmentation?*

One could avoid the problem of the unlikelihood of VLM binaries surviving the dynamics of an ejection or cluster decay if one simply produces VLM binaries in the same fashion that more massive binaries are thought to form. This is commonly thought to be through the fragmentation of molecular cloud cores. A fragmenting very low mass molecular cloud core could directly produce a VLM binary without evoking any ejection or decay processes.

It would be interesting to see if we can approximate a VLM binary semi-major axis distribution produced by fragmentation by scaling distributions of more massive binaries. If we assume M_{tot}/a_o is roughly constant for wide binaries (see Figure 15), then we expect the initial a_o distribution to be somewhat tighter for VLM binaries compared to more massive binaries. We can estimate the a_o for solar mass binaries from the well known young T-Tauri star a distributions. Young T-Tauri binaries are strongly suspected to have formed by fragmentation (White & Ghez 2001). We can utilize a HST sample of 29 T-Tauri binary systems in Taurus to produce an initial separation distribution. Such a distribution from the sample of White & Ghez (2001) has an a_o peak at ~ 30 AU (as also found by Leinert et al. (1993); Ghez et al. (1993)). We can scale this to match our observed VLM binary peak of ~ 4 AU by simply scaling the distribution by $a_{o_{VLM}} \sim 0.13(a_{o_{TTau}})$. Similarly we can scale the masses of the T Tauri binaries to also match our mean VLM binary mass of $\sim 0.15 M_{\odot}$ by multiplying by the same factor of 0.13. In this manner we have created a plausible fragmentation-produced VLM a_o distribution. However, we have assumed that the other properties of the distribution (such as the FWHM and tail distributions) can be scaled along with the mean a_o and M_{tot}. Assuming such a scaling is valid globally, we see that this fragmentation $a_{o_{VLM}}$ distribution has $\sim 26\%$ of systems wider than ~ 40 AU. Hence if our observed VLM distribution is to match this scaled fragmentation a_o distribution, we would expect ~ 9 of the 34 VLM/brown dwarf systems observed (see Table 4) to have separations greater than 40 AU. However, from Figure 15 *no VLM systems are observed to have separations greater than 16 AU*. Therefore, it appears very hard to explain the total lack of systems with separations greater than 16 AU by scaling the observed a_o distribution of T-Tauri stars. In other words, if we scale the distribution to match the VLM ~ 4 AU peak we over-produce wide systems (26% of systems wider than 40 AU) compared to observations. It may be that our "toy model" of simply scaling the T Tauri a_o distribution is too simple an approach, but, it is a first step which shows that such a sharp cut-off ($a_o < 16$ AU) is not easily produced by a fragmentation distribution. Detailed fragmentation simulations at the lowest masses will be required to prove whether fragmentation can produce the VLM binary separation distribution observed.

6.1.5. *What effect does an ejection "kick" have on the binary distribution?*

Assuming (as has been suggested by Reid et al. (2002); Bate et al. (2002)) that eventually a close multiple encounter ejects VLM ($< 0.185 M_{\odot}$) binaries, it would be interesting to see if such an "ejected" VLM binary distribution would have a maximum separation of ~ 16 AU as observed. The full dynamical modeling of the effect of a binary's ejection from a mini-cluster is beyond the scope of this paper. However, we can simply explore, as a "toy-model", the possibility that the ejection process provides a hard differential velocity kick of order ~ 3km/s to the two components of an ejected VLM binary. We take the value of ~ 3 km/s since this is the value calculated for the ejection velocity of on average more massive single objects from a dissolving mini-cluster (Sterzik & Durisen 1998; Reipurth & Clarke 2001). We assume, this may be of the right order of magnitude for the differential velocity kick between the VLM members of the ejected binary. We caution that this is only a simple toy-model, the true differential velocity applied during the ejection can only be calculated by detailed simulations of each ejection event.

In our simple toy-model ejection only binaries with $V_{esc} \gtrsim 3.0$ km/s will survive the ejection process. Moreover, systems that are more tightly bound than $V_{esc} = 3.0$ will hardly be effected by such a kick in the tidal limit of Weinberg et al. (1987). To survive in the general galactic field we see (from Figure 15) $V_{esc} \gtrsim 0.6$ km/s. Hence one may expect today's population of VLM binaries to all have $V_{esc_{VLM}} \gtrsim (3.0 + 0.6)$ km/s.

It is very interesting to note that we "observe" (from figure 15) $V_{esc} \gtrsim 3.8$ km/s for wide VLM binaries which is similar to the "predicted" value of $V_{esc_{VLM}} \gtrsim 3.6$ km/s. Therefore, the observed cut-off at 16 AU could be produced by a population of VLM binaries where each system has been subjected to a differential kick of ~ 3 km/s in the ejection process. *We conclude that it is possible to produce the observed distribution of semi-major axes for VLM binaries by applying a strong differential velocity kick to each binary in the distribution. However, it is still not clear if a VLM binary frequency of* $9 - 15\%$ *could be produced by ejection, since ejection of a VLM tight binary may be a very rare event.*

7. FUTURE OBSERVATIONS

Future observations of all of these binaries should determine if there is still Li present in their spectrum. The most useful Li observation would spatially resolve both components in the visible spectrum. Currently there is no visible wavelength AO systems capable of guiding on a $V \sim 20$ source and obtaining resolutions better than $0.1''$ in the optical (Close 2000, 2002). Therefore, we will have to carry out such observations from space with HST/STIS perhaps. Trigonometric parallax measurements should also be obtained in the near future. Within the next few years one should also be able to measure the masses of both components of several of these systems as they complete a significant fraction of their orbit. Hence, further observations of these systems are a high priority for the calibration of the brown dwarf mass-age-luminosity relation. Continued searches for new VLM binaries will help define this very interesting and important binary population with greater precision.

8. CONCLUSIONS ABOUT THE VLM POPULATION IN GENERAL

Based on all 34 VLM ($M_{tot} < 0.185 M_{\odot}$) systems currently known from this work and that of Basri & Martín (1999); Martín, Brandner, & Basri (1999); Koerner et al. (1999); Reid et al. (2001a); Lane et al. (2001); Potter et al. (2002a); Burgasser et al. (2003); Bouy et al. (2003), we find the following general characteristics:

- VLM binaries are tight (peak separation ~ 4 AU) with no systems wider than 16 AU (this is ~ 10 times tighter than the slightly more massive M0-M4 binaries);
- they tend to have nearly equal mass companions ($q \sim 0.9$) with no detected companions below $\sim 70\%$ of the primary's mass;
- they have a corrected binary frequency of $15 \pm 7\%$ for spectral types M8-L0.5, and $9^{+15}_{-4}\%$ for T dwarf binaries (Burgasser et al. 2003) for separations $a > 2.6$ AU. This is less than the $32 \pm 9\%$ binary frequency of M0-M4 binaries (Fischer & Marcy 1992) and the $\sim 50\%$ binarity of G dwarf binaries (Duquennoy & Mayor 1991) for similar separations.

We find the formation of such a VLM distribution to be problematic with current simulations of binary star formation.

- Ejecting VLM binaries from their formation mini-clusters (Reipurth & Clarke 2001) can likely produce the observed cut-off in separation at 16 AU, but ejection simulations (Bate et al. 2002) produce a binarity of $\lesssim 5\%$ which is smaller than the $\sim 9-15\%$ binarity observed.
- If we ignore ejection and assume that these VLM binaries are instead the residual (most massive) system remaining from the dynamical decay of the mini-cluster one can likely also reproduce the tight cut-off at 16 AU. But the strong bias to higher masses in the final binary predicts that too few VLM binaries would be made in this fashion –assuming each component is picked randomly from the IMF (Sterzik & Durisen 1998; Durisen, Sterzik, & Pickett 2001).
- We briefly look at a "toy-model" of a VLM binary population produced by fragmentation. It appears that simply scaling an observed fragmentation produced T-Tauri distribution to force a peak at 4 AU produces systems with separations much greater than the 16 AU cut-off observed.

Hence, it is not obvious that the characteristics of the VLM binary distribution are accurately predicted by any of these methods. Future detailed modeling (taking into account circumstellar gas disks and their effects on dynamical interactions/ejections) will be required to see if ejection or dynamical decay can be common enough to explain the $\sim 9 - 15\%$ binarity of VLM systems. Future detailed fragmentation simulations of the smallest cores will be needed to discern if some type of truncation occurs at low masses that limits VLM binaries to separations of less than 16 AU.

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TABLE 1
M8.0-L0.5 STARS OBSERVED WITH NO LIKELY PHYSICAL COMPANIONS BETWEEN 0.1″-15″

2MASS	other name	K_s	SpT	Ref.
2MASSW J0027559+221932	LP 349-25	9.56	M8.0	1
2MASSW J0140026+270150		11.44	M8.5	1
2MASSI J0149089+295613		11.99	M9.5	1
2MASSW J0253202+271333		11.45	M8.0	1
2MASSW J0320597+185423	LP412-31	10.57	M9.0	1
2MASSI J0335020+234235		11.26	M8.5	1
2MASSW J0350573+181806	LP 413-53	11.76	M9.0	1
2MASSW J0354013+231633		11.97	M8.5	1
2MASSW J0810586+142039		11.61	M9.0	1
2MASSW J0853361-032931	LHS 2065	9.98	M9.0	2
2MASSW J0928256+423054		11.97	M8.0	3
2MASSW J1019568+732408		11.78	M8.0	3
2MASSW J1124048+380805		11.57	M8.0	3
2MASSW J1224522-123835	BRI 1222-1221	11.37	M9.0	2
2MASSP J1309219-233035		10.67	M8.0	4
2MASSW J1403223+300755		11.63	M8.5	1
2MASSW J1421314+182740		11.93	M9.5	1
2MASSW J1444171+300214	LP326-21	10.57	M8.0	1
2MASSW J1457396+451716		11.92	M9.0	1
2MASSI J1501081+225001	TVLM 513-46546	10.72	M8.5	5
2MASSW J1551066+645704		11.73	M8.5	1
2MASSW J1553199+140033		11.85	M9.0	1
2MASSW J1627279+810507		11.87	M9.0	1
2MASSW J1635192+422305		11.80	M8.0	1
2MASSW J1707183+643933		11.39	M9.0	1
2MASSW J1733189+463359		11.86	M9.5	1
2MASSI J2234138+235956		11.81	M9.5	1
2MASSI J2334394+193304		11.64	M8.0	1
2MASSW J2347368+270206		12.00	M9.0	1
2MASSW J2349489+122438	LP 523-55	11.56	M8.0	1

References. — (1)Gizis et al. (2000); (2)Kirkpatrick et al. (1995); (3)Cruz et al. (2003); (4)Kirkpatrick et al. (1997); (5)Tinney et al. (1993)

Table 2
The binary systems observed

System	ΔJ	ΔH	$\Delta K'$	Sep. ($''$)	PA	Age (Gyr)
2MASSW J0746425+200032[a]	0.60 ± 0.20	0.48 ± 0.15	0.44 ± 0.15	0.121 ± 0.008[c]	$85.7 \pm 1.45°$[c]	$5.0^{+2.5}_{-4.15}$
2MASSW J1047127+402644[b]	0.85 ± 0.25	0.91 ± 0.20	0.50 ± 0.15	0.122 ± 0.008[d]	$328.36 \pm 3.75°$[d]	$5.0^{+2.5}_{-4.4}$
LHS 2397a[g]	3.83 ± 0.60	3.15 ± 0.30	2.77 ± 0.10	0.207 ± 0.007[c]	$151.98 \pm 1.20°$[c]	$7.2^{+4.8}_{-5.2}$
2MASSW J1127534+741107	0.33 ± 0.11	0.27 ± 0.10	0.25 ± 0.07	0.246 ± 0.008[c]	$80.23 \pm 1.72°$[c]	$3.0^{+4.5}_{-2.4}$
2MASSW J1311391+803222	0.13 ± 0.10	0.15 ± 0.09	0.14 ± 0.05	0.267 ± 0.006[d]	$168.15 \pm 0.48°$[d]	$5.0^{+2.5}_{-4.4}$
2MASSW J1426316+155701	0.78 ± 0.05	0.70 ± 0.05	0.65 ± 0.10	0.152 ± 0.006[e]	$344.1 \pm 0.7°$[e]	$0.8^{+6.7}_{-0.2}$
2MASSW J2140293+162518	0.77 ± 0.05	0.73 ± 0.04	0.75 ± 0.04	0.155 ± 0.005[f]	$134.30 \pm 0.5°$[f]	$3.0^{+4.5}_{-2.4}$
2MASSW J2206228-204705	0.17 ± 0.04	0.08 ± 0.03	0.08 ± 0.03	0.168 ± 0.007[f]	$68.2 \pm 0.5°$[f]	$3.0^{+4.5}_{-2.4}$
2MASSW J2331016-040618	2.78 ± 0.04	2.64 ± 0.05	2.44 ± 0.03	0.573 ± 0.008[f]	$302.6 \pm 0.4°$[f]	$5.0^{+2.5}_{-4.4}$

[a]discovery paper Reid et al. (2001a)

[b]discovery paper Reid et al. (2002)

[c]observations made on Feb 7, 2002 UT

[d]observations made on April 25, 2002 UT

[e]observations made on June 20, 2001 UT

[f]observations made on Sept 20, 2001 UT

[g]discovery paper Freed, Close, & Siegler (2003)

Table 3
Summary of the new binaries' A & B components

Name	J	H	Ks	M_{K_s}[c]	SpT[a]	Est. Mass[b]	Est. D (pc)[c]	Sep. (AU)	P (
2M0746A	12.23 ± 0.083	11.53 ± 0.07	11.04 ± 0.07	10.58 ± 0.07	L0.5	$0.082^{+0.001}_{-0.004}$	12.34 ± 0.05[e]	1.47 ± 0.11	11
2M0746B	12.83 ± 0.21	12.01 ± 0.16	11.48 ± 0.16	11.0 ± 0.17	L2	$0.078^{+0.001}_{-0.009}$			
2M1047A	12.85 ± 0.08	12.09 ± 0.07	11.80 ± 0.07	9.95 ± 0.39	M8	$0.092^{+0.009}_{-0.012}$	23.4 ± 4.3	2.9 ± 0.6	11
2M1047B	13.70 ± 0.26	13.00 ± 0.21	12.31 ± 0.16	10.46 ± 0.42	L0	$0.084^{+0.006}_{-0.016}$			
LHS 2397aA	11.86 ± 0.05	11.32 ± 0.05	10.80 ± 0.03	10.03 ± 0.09	M8	$0.090^{+0.004}_{-0.001}$	14.3 ± 0.4[e]	3.86 ± 0.18	22
LHS 2397aB	15.69 ± 0.60	14.47 ± 0.30	13.57 ± 0.10	12.80 ± 0.12	L7.5	$0.068^{+0.001}_{-0.007}$			
2M1127A	13.66 ± 0.06	12.99 ± 0.05	12.60 ± 0.05	9.96 ± 0.37	M8	$0.092^{+0.009}_{-0.012}$	33.67 ± 5.9	8.31 ± 1.49	57
2M1127B	13.99 ± 0.13	13.26 ± 0.11	12.85 ± 0.08	10.21 ± 0.38	M9	$0.087^{+0.007}_{-0.013}$			
2M1311A	13.49 ± 0.06	12.82 ± 0.05	12.39 ± 0.04	10.07 ± 0.37	M8.5	$0.089^{+0.008}_{-0.011}$	29.1 ± 5.1	7.7 ± 1.3	51
2M1311B	13.62 ± 0.11	12.97 ± 0.10	12.53 ± 0.07	10.21 ± 0.38	M9	$0.087^{+0.007}_{-0.013}$			
2M1426A	13.30 ± 0.04	12.63 ± 0.04	12.18 ± 0.05	10.09 ± 0.37	M8.5	$0.088^{+0.009}_{-0.010}$	26.1 ± 4.5	3.9 ± 0.7	19
2M1426B	14.08 ± 0.06	13.33 ± 0.06	12.83 ± 0.11	10.74 ± 0.38	L1	$0.076^{+0.008}_{-0.014}$			
2M2140A	13.37 ± 0.04	12.71 ± 0.04	12.22 ± 0.04	10.17 ± 0.37	M9	$0.088^{+0.007}_{-0.012}$	25.6 ± 4.4	3.9 ± 0.6	19
2M2140B	14.14 ± 0.06	13.44 ± 0.05	12.97 ± 0.05	10.92 ± 0.37	L2	$0.078^{+0.004}_{-0.020}$			
2M2206A	13.10 ± 0.04	12.46 ± 0.04	12.06 ± 0.04	9.93 ± 0.37	M8	$0.092^{+0.009}_{-0.011}$	26.7 ± 4.5	4.4 ± 0.7	22
2M2206B	13.27 ± 0.05	12.54 ± 0.05	12.14 ± 0.05	10.01 ± 0.37	M8	$0.091^{+0.008}_{-0.011}$			
2M2331A	13.02 ± 0.04	12.38 ± 0.04	12.03 ± 0.04	9.93 ± 0.08	M8.0	$0.093^{+0.002}_{-0.002}$	26.2 ± 0.6[e]	15.0 ± 0.37	15
2M2331B	15.80 ± 0.05	15.02 ± 0.06	14.47 ± 0.05	12.37 ± 0.12	L7	$0.067^{+0.002}_{-0.013}$			

[a]Spectral types estimated by $3.97 \mathrm{x} M_{Ks} - 31.67$ (Dahn et al. 2002; Siegler et al. 2003) with ± 1.5 spectral subclasses of error in estimates (note a value of SpT=10 is defined as L0 in the above equation).

[b]Masses (in solar units) from the models of Chabrier et al. (2000) –see Figure 3.

[c]Photometric distances estimated for the primaries by $M_{Ks} = 7.71 + 2.14(J - Ks)$ which is valid for $M7 < SpT < L1$ (Siegler 2003).

[d]Periods estimated assuming face-on circular orbits. In the cases of 2M0746 and LHS 2397a, the larger of the 2 observed separ (2.7 AU & 3.86 AU from Reid et al. (2001a) and Freed, Close, & Siegler (2003), respectively) have been used to more accurately est the period.

[e]These systems have trigonometric parallaxes.

Table 4

All Known Resolved VLM Binaries[e]

Name	Sep. AU	Est. SpT_A/SpT_B	Est. M_A $M_\odot$	Est. M_B $M_\odot$	Est. Period[b] yr	Ref.[c]
PPL 15[a]	0.03	M7/M8	0.07	0.06	5.8 days	0
Gl 569B	1.0	M8.5/M9.0	0.063	0.06	3	1,2
SDSS 2335583-001304	1.1?	L1?/L4?	0.079	0.074	3	12
2MASSW J1112256+354813	1.5	L4/L6	0.073	0.070	5	12
2MASSI J1534498-295227	1.8	T5.5/T5.5	0.05	0.05	8	9
2MASSW J0856479+223518	2.0	L5?/L8?	0.071	0.064	8	12
DENIS-P J185950.9-370632	2.0	L0/L3	0.084	0.076	7	12
HD130948B	2.4	L2/L2	0.07	0.06	10	3
2MASSW J0746425+200032	2.7	L0.5/L2	0.082	0.078	12	4 & this paper
2MASSW J1047127+402644	2.7	M8/L0	0.092	0.084	11	8 & this paper
DENIS-PJ035726.9-441730	2.8	L2/L4	0.078	0.074	12	12
2MASSW J0920122+351742	3.2	L6.5/L7	0.068	0.068	16	4
LP415-20	3.5	M7/M9.5	0.095	0.079	15	11, this survey
2MASSW J1728114+394859	3.7	L7/L8	0.069	0.066	19	12
LHS 2397a	3.9	M8/L7.5	0.090	0.068	22	7,this paper
2MASSW J1426316+155701	3.9	M8.5/L1	0.088	0.076	19	this paper
2MASSW J2140293+162518	3.9	M9/L2	0.092	0.078	22	this paper
2MASSW J2206228-204705	4.4	M8/M8	0.092	0.092	22	this paper
2MASSs J0850359+105716	4.4	L6/L8	0.05	0.04	30	4
2MASSW J1750129+442404	4.8	M7.5/L0	0.095	0.084	25	11, this survey
DENIS-P J1228.2-1547	4.9	L5/L5	0.05	0.05	34	10
2MASSW J1600054+170832	5.0	L1/L3	0.078	0.075	29	12
2MASSW J1239272+551537	5.1	L5/L5	0.071	0.071	31	12
2MASSI J1553022+153236	5.2	T7/T7.5	0.040	0.035	43	9
2MASSW J1146345+223053	7.6	L3/L4	0.055	0.055	63	6
2MASSW J1311391+803222	7.7	M8.5/M9	0.089	0.087	51	this paper
2MASSW J1127534+741107	8.3	M8/M9	0.092	0.087	57	this paper
LP475-855	8.3	M7.5/M9.5	0.091	0.080	58	11, this survey
DENIS-P J0205.4-1159	9.2	L7/L7	0.07	0.07	75	6
2MASSW J2101349+175611	9.6	L7/L8	0.068	0.065	82	12
2MASSW J2147436+143131	10.4	L0/L2	0.084	0.078	83	12
2MASSW J1449378+235537	11.7	L0/L3	0.084	0.075	100	12
DENIS-P J144137.3-094559	13.5	L1/L1	0.079	0.079	124	12
2MASSW J2331016-040618	15.0	M8.0/L7	0.093	0.067	159	this paper

[a]PPL 15 is a spectroscopic binary (Basri & Martín 1999)

[b]This "period" is simply an estimate assuming a face-on circular orbit

[c]REFERENCES–(0)Basri & Martín (1999); (1) Kenworthy et al. (2001); (2) Lane et al. (2001); (3) Potter et al. (2002a); (4)Reid et al. (2001a); (5) Martín, Brandner, & Basri (1999); (6) Koerner et al. (1999); (7) Freed, Close, & Siegler (2003); (8) Reid et al. (2002); (9) Burgasser et al. (2003); (10) Martín, Brandner, & Basri (1999); (11) Siegler et al. (2003); (12) Bouy et al. (2003)

[d]Gl 569B and HD130948B are binary brown dwarfs that orbit normal stars, for AO observations these bright primary stars were guided on, not the brown dwarfs

[e]We define VLM binaries as 2 star systems where $M_{tot} < 0.185 M_\odot$. Very young evolving systems (like GG TauBaBb (White & Ghez 2001)) are not included, nor are over-luminous systems which are not resolved into binaries.

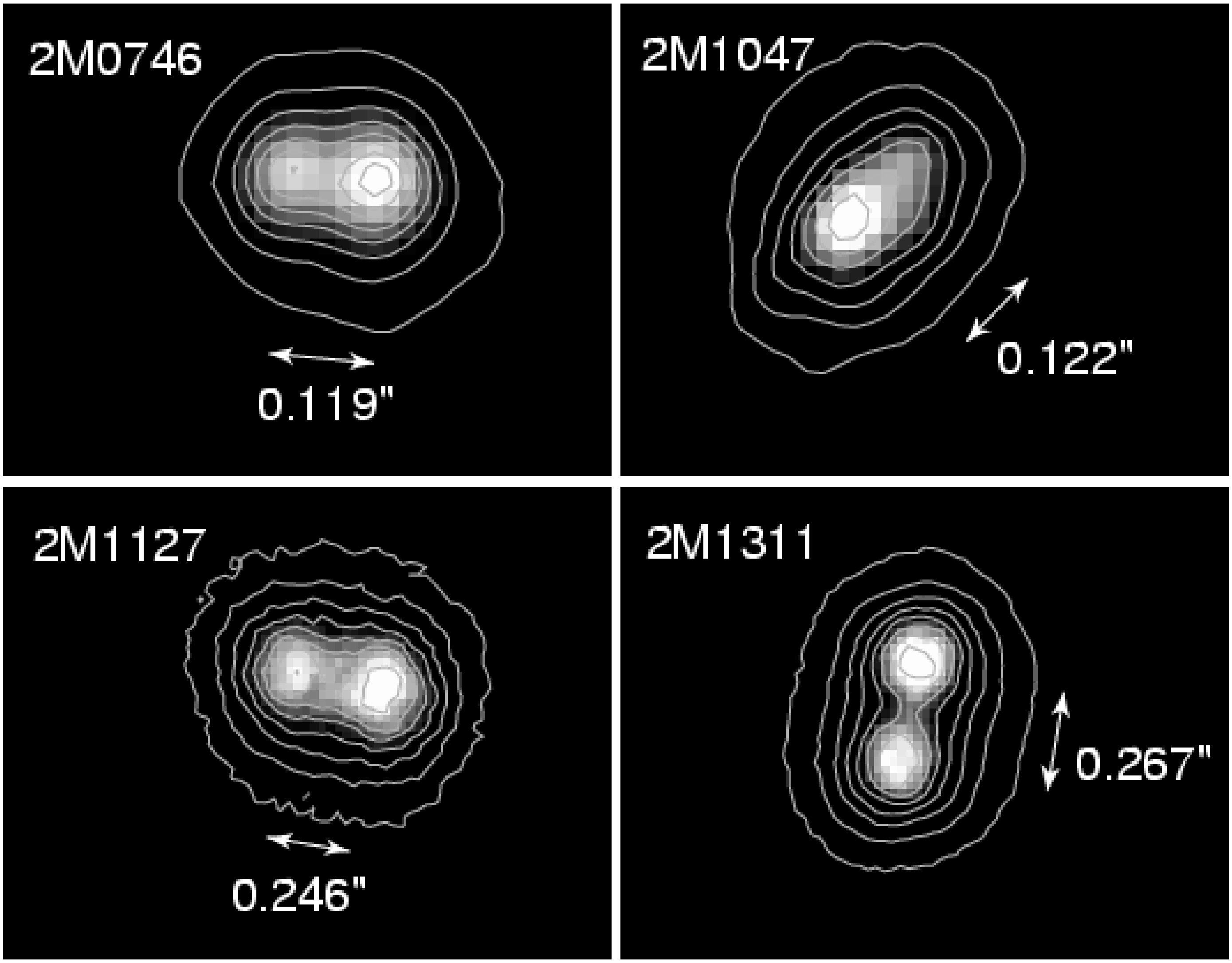

Fig. 1.— The 12x10s K' image of the L0.5 2MASSW J0746425+200032 binary (which is the one overlap object between our study and that of Reid et al. (2001a)). Note the very different position ($PA = 85.7°$, $sep = 0.121'' = 1.49$ AU on 2002/2/7) of our image compared to the PA=168.8° sep 2.7 AU published by Bouy et al. (2003) from HST observations of Reid et al. (2001a) at 2000/4/15. This suggests that the orbit could have a period of $\sim$ 4yr. In the near future this system could have an orbital solution. At a resolution of $< 0.1''$ both components are clearly visible. We also show K' images of the new binaries 2MASSW J1047127+402644, 2MASSW J1127534+741107, & 2MASSW J1311391+803222. The pixels are $0.199''\mathrm{pix}^{-1}$. The contours are linear at the 90, 75, 60, 45, 30, 15, and 1% levels. North is up and east left in each image.

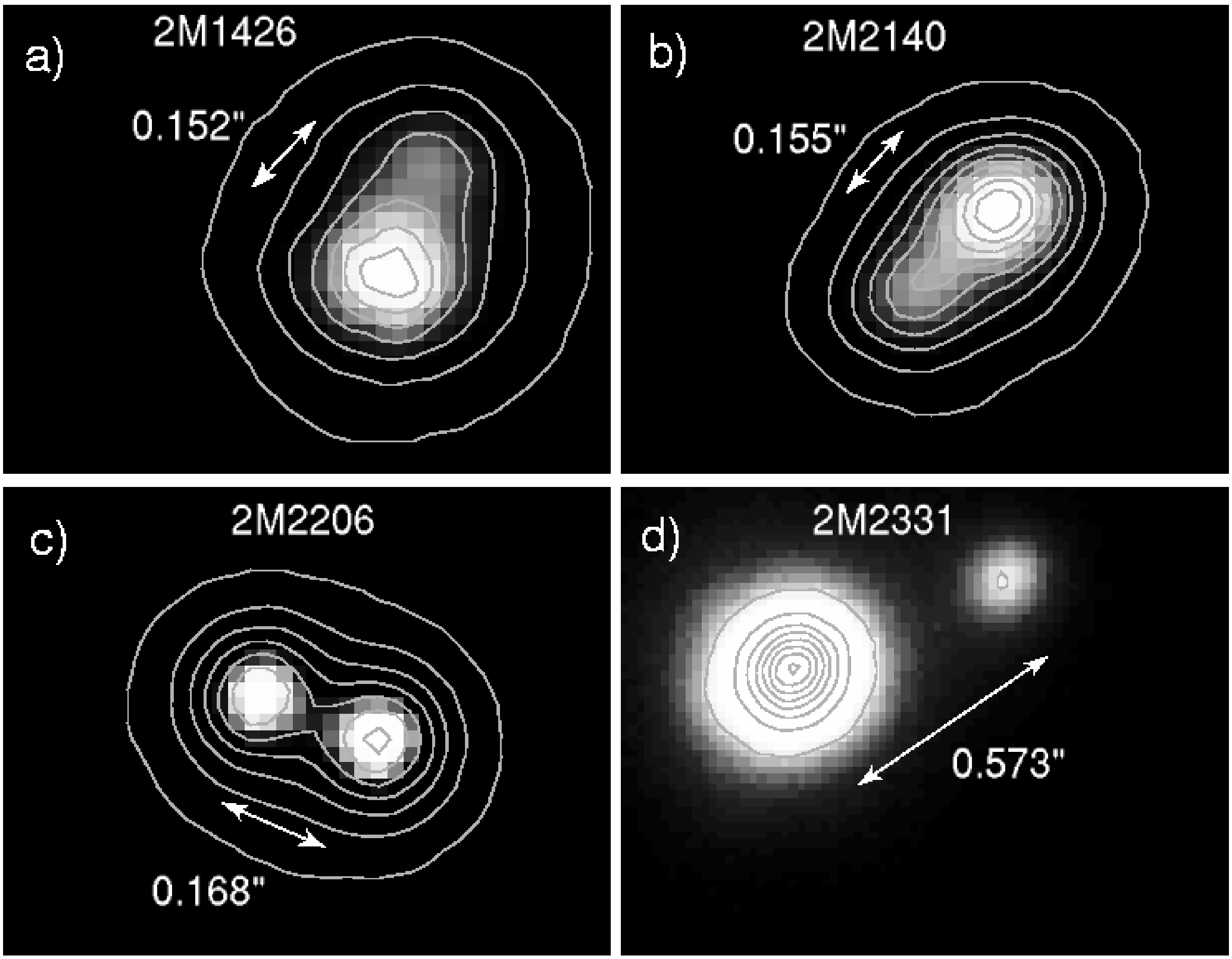

Fig. 2.— In figure (a) we see the 12x10s K' image of the 2MASSJ 1426316+155701 binary discussed in Close et al. (2002b) at a resolution of 0.131″. In Figures (b-d) we show K' images of the binaries 2MASSW J2140293+162518, 2MASSWJ 2206228-204705, and 2MASSWJ 2331016-040618, respectively. The pixels are 0.0199″pix^{-1}. The contours are linear at the 90, 75, 60, 45, 30, 15, and 1% levels. North is up and east left in each image.

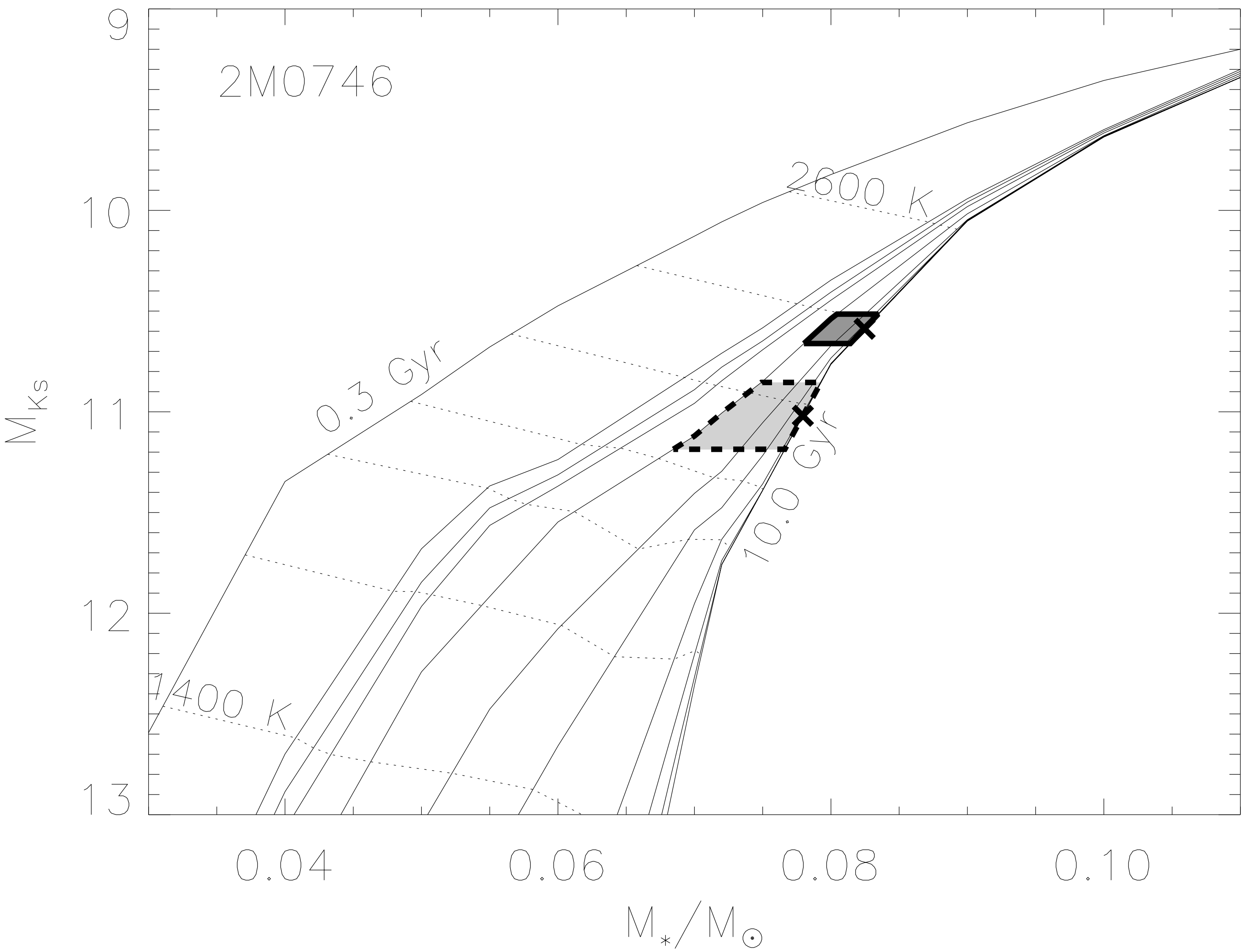

Fig. 3.— The latest Chabrier et al. (2000) DUSTY evolutionary models are shown custom integrated over the Ks bandpass. The locations of the 2 components of 2M0746 are indicated by the crosses. The polygon encloses the error in the M_{Ks} and age range $0.6 - 7.5$ Gyr of the system. The M_{Ks} of each secondary is determined by the addition of ΔKs plus the M_{Ks} of the primary. The errors for the primary are enclosed by the upper polygon (outlined by a solid thick line), the secondary is bounded by the lower polygon (outlined by a thick dashed line). The models suggest a primary mass of 0.082 $M_\odot$ with a range $0.078 - 0.083 M_\odot$ with temperatures of 2375 K (2323-2409K). For the secondary the models suggest a mass of $0.078 M_\odot$ with a range $0.068 - 0.079 M_\odot$ with temperatures of 2173K (2034-2252 K). The isochrones plotted are 0.3, 0.6, 0.65, 0.7, 0.85, 1.2, 1.7, 3.0, 5.0, 7.5, & 10.0 Gyr. The isotherms run in equal intervals from 2600 K to 1400 K in steps of 200 K.

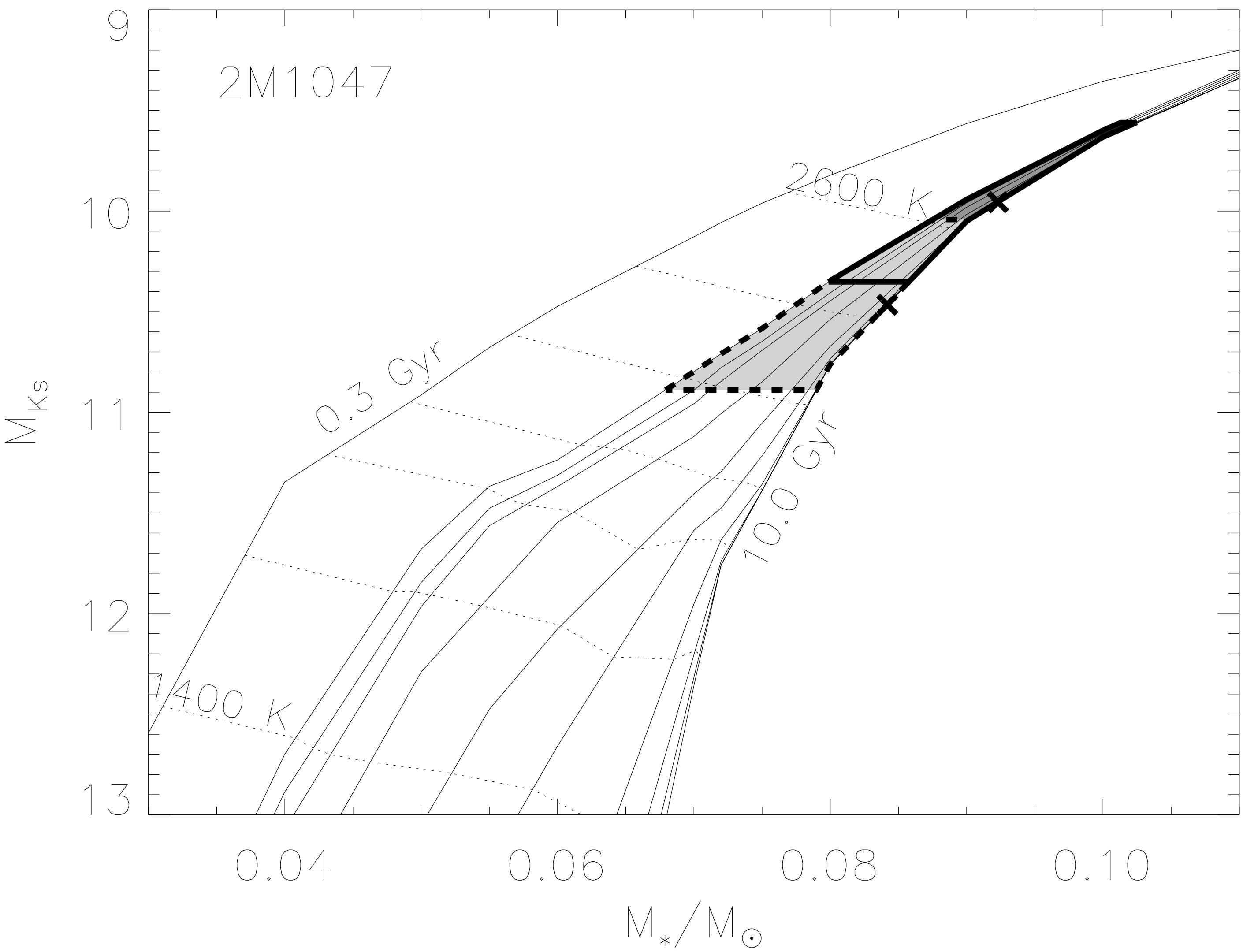

FIG. 4.— The same as figure 3 except for 2M1047. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.092 $M_\odot$ with a range $0.079 - 0.102 M_\odot$ with temperatures of 2660 K (2460-2830K). For the secondary the models suggest a mass of $0.084 M_\odot$ with a range $0.068 - 0.090 M_\odot$ with temperatures of 2430K (2164-2625 K).

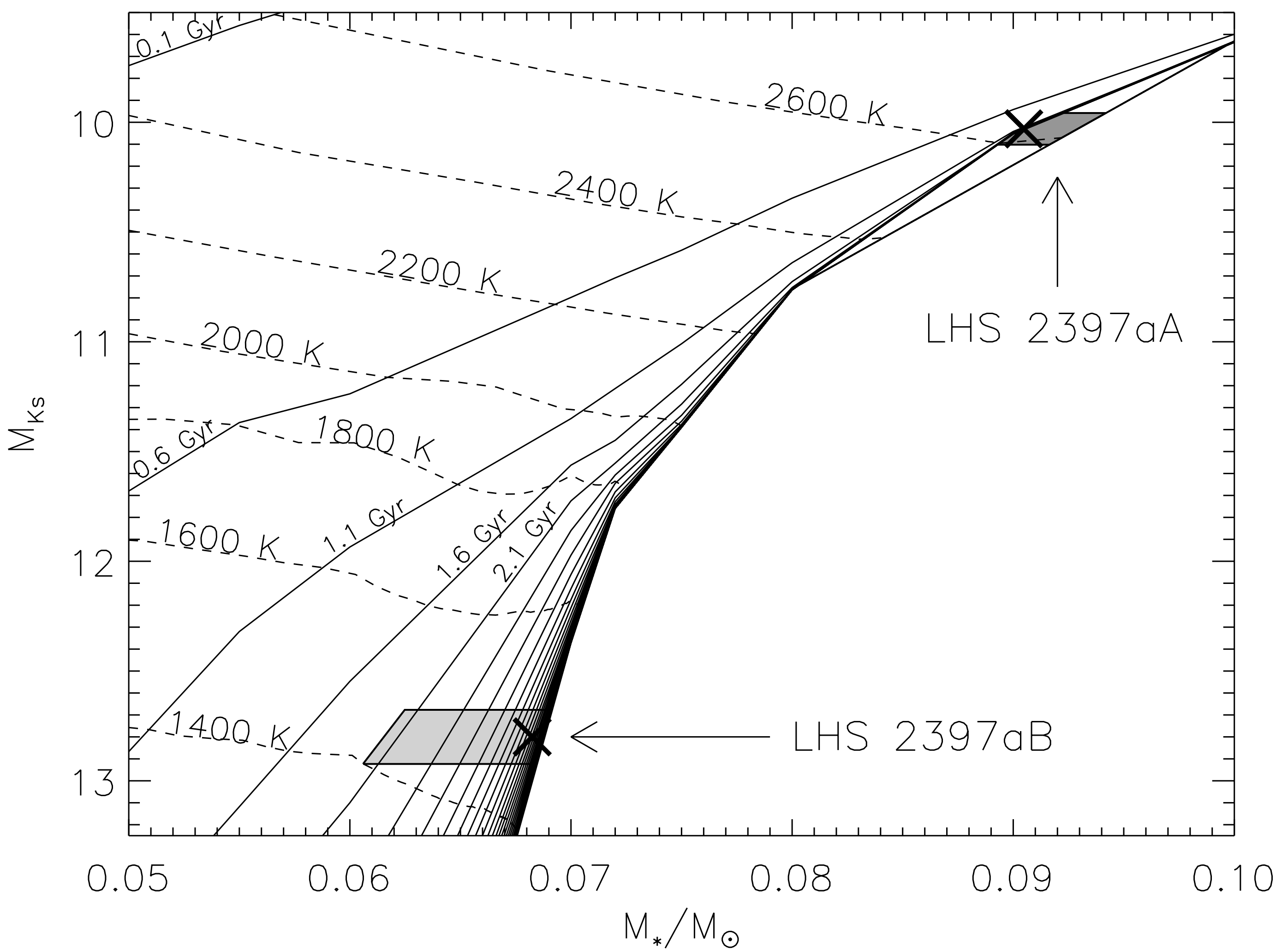

FIG. 5.— Figure 3 from Freed, Close, & Siegler (2003). Note that the isochrones are different for this plot compared to all the other plots in this paper (but the isotherms are the same). More detail about LHS 2397a can be found in Freed, Close, & Siegler (2003). LHS 2397aB (mass 0.068 $M_{\odot}$) is one of the tightest brown dwarf companions ever to be imaged around a star.

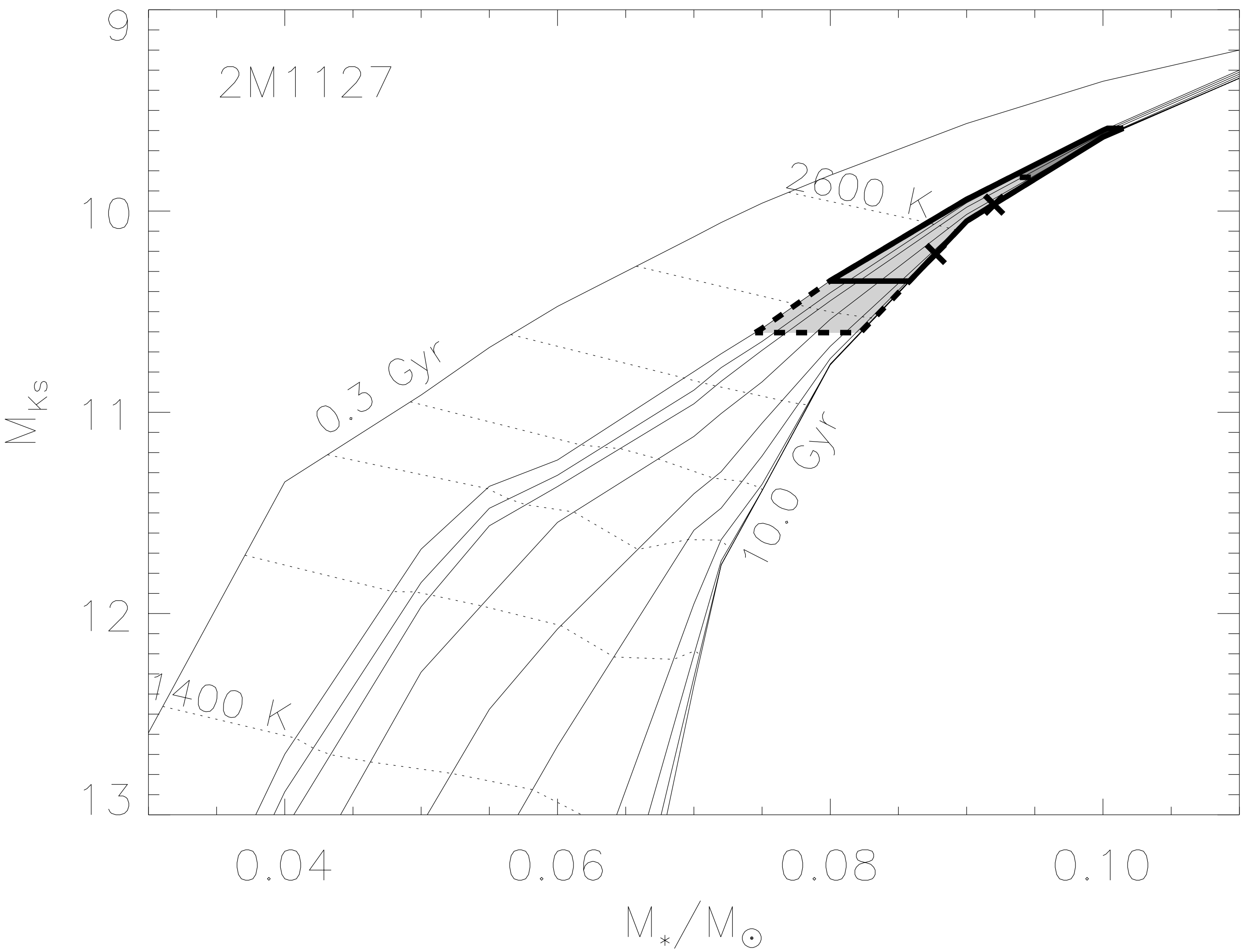

FIG. 6.— The same as for figure 3 except for 2M1127. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.092 $M_\odot$ with a range $0.080-0.101 M_\odot$ with temperatures of 2650 K (2460-2810K). For the secondary the models suggest a mass of $0.087 M_\odot$ with a range $0.074-0.095 M_\odot$ with temperatures of 2540K (2330-2710 K).

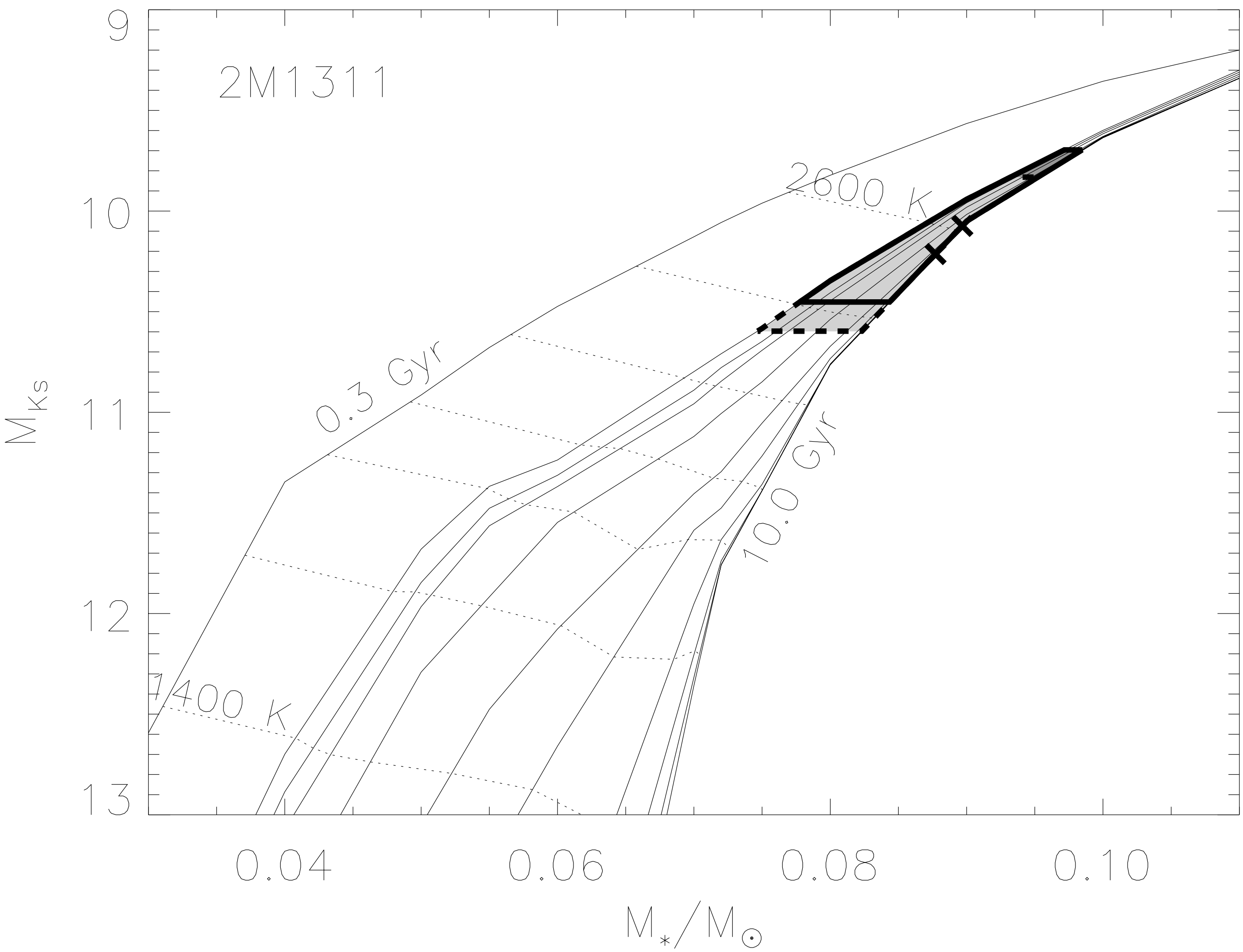

FIG. 7.— The same as for figure 3 except for 2M1311. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.089 $M_\odot$ with a range $0.078-0.098M_\odot$ with temperatures of 2610 K (2400-2760K). For the secondary the models suggest a mass of $0.088M_\odot$ with a range $0.074-0.095M_\odot$ with temperatures of 2540K (2331-2710 K).

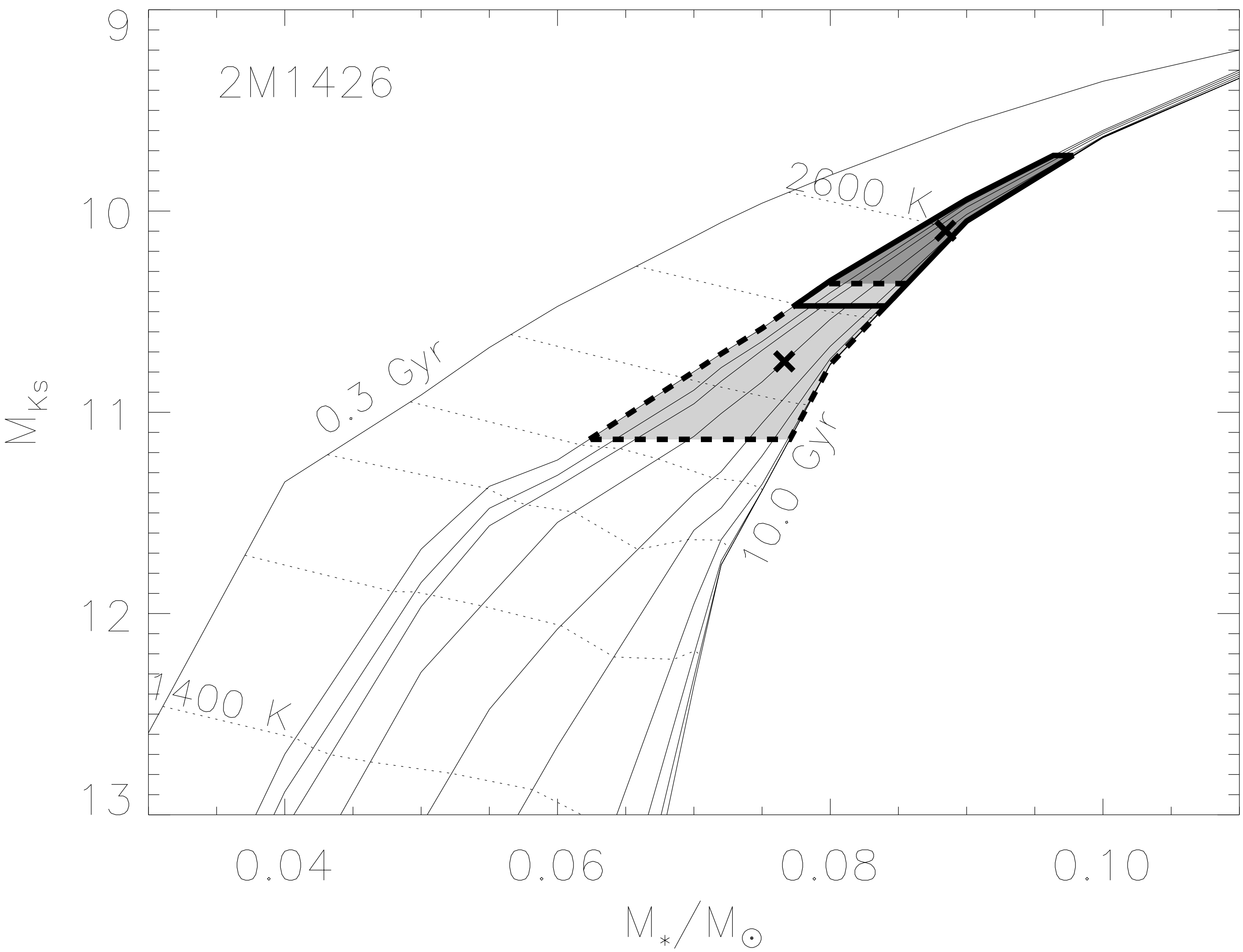

FIG. 8.— The same as for figure 3 except for 2M1426. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.088 $M_\odot$ with a range $0.077-0.097 M_\odot$ with temperatures of 2560 K (2400-2750K). For the secondary the models suggest a mass of $0.076 M_\odot$ with a range $0.062-0.085 M_\odot$ with temperatures of 2280K (2016-2480 K).

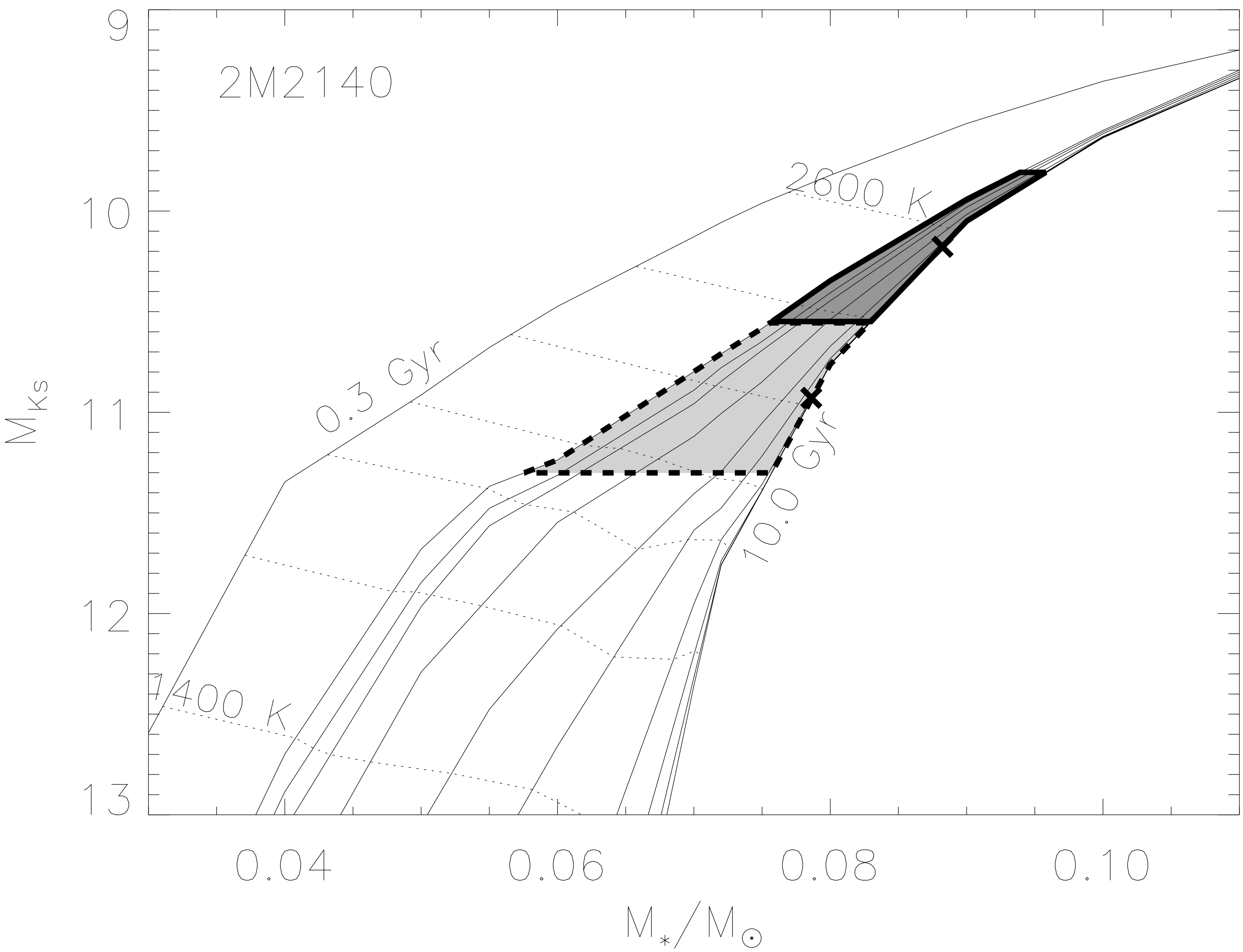

FIG. 9.— Same as for figure 3 except for 2M2140. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.088 $M_\odot$ with a range $0.075-0.095M_\odot$ with temperatures of 2560 K (2360-2720K). For the secondary the models suggest a mass of $0.078M_\odot$ with a range $0.057-0.083M_\odot$ with temperatures of 2210K (1880-2390 K).

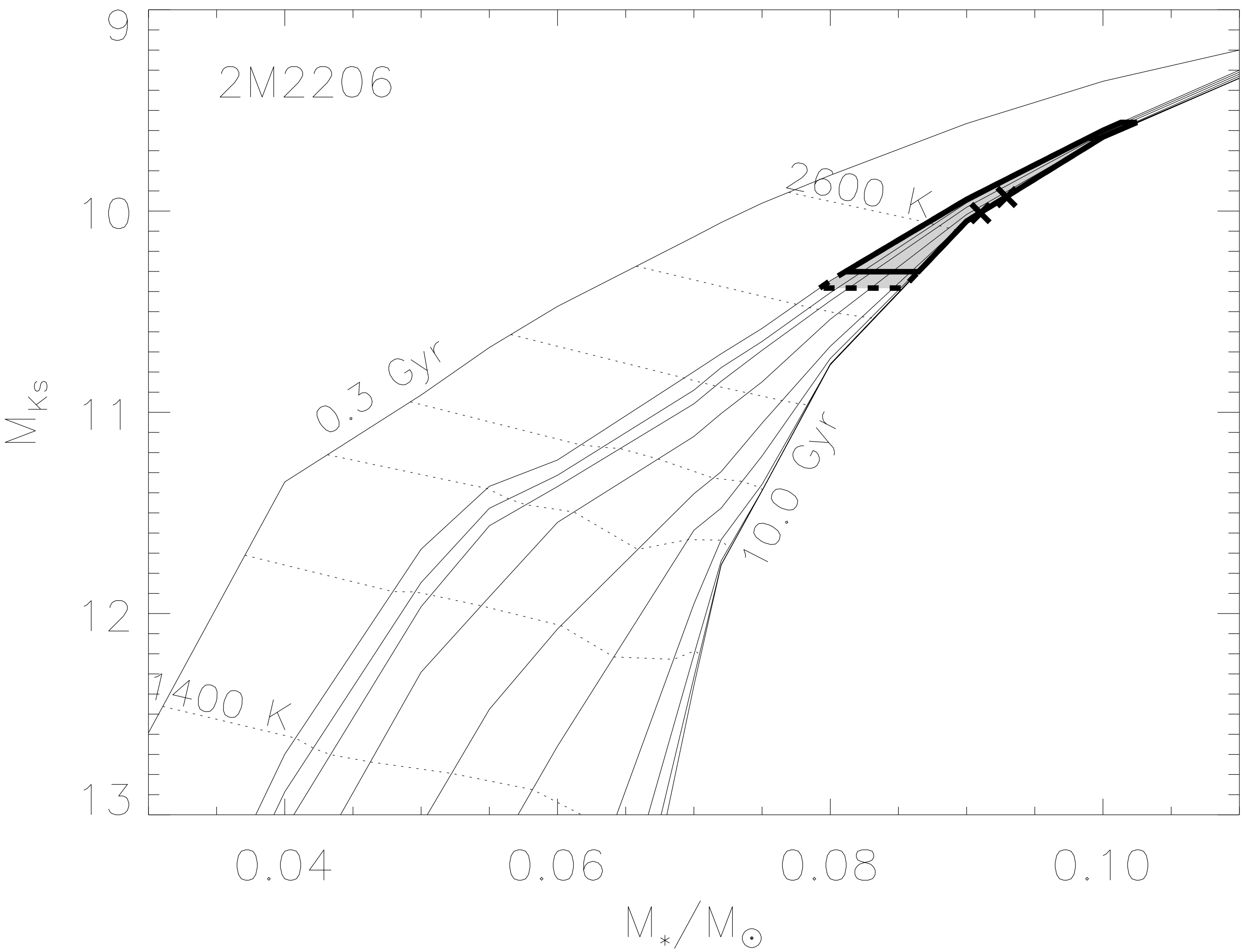

FIG. 10.— The same as for figure 3 except for 2M2206. Note the larger errors in M_{Ks} compared to 2M0746 since we have to currently rely on a photometric parallax for this system. The models suggest a primary mass of 0.092 $M_\odot$ with a range $0.081-0.102 M_\odot$ with temperatures of 2670 K (2480-2830K). For the secondary the models suggest a mass of $0.091 M_\odot$ with a range $0.079-0.100 M_\odot$ with temperatures of 2640K (2440-2790 K).

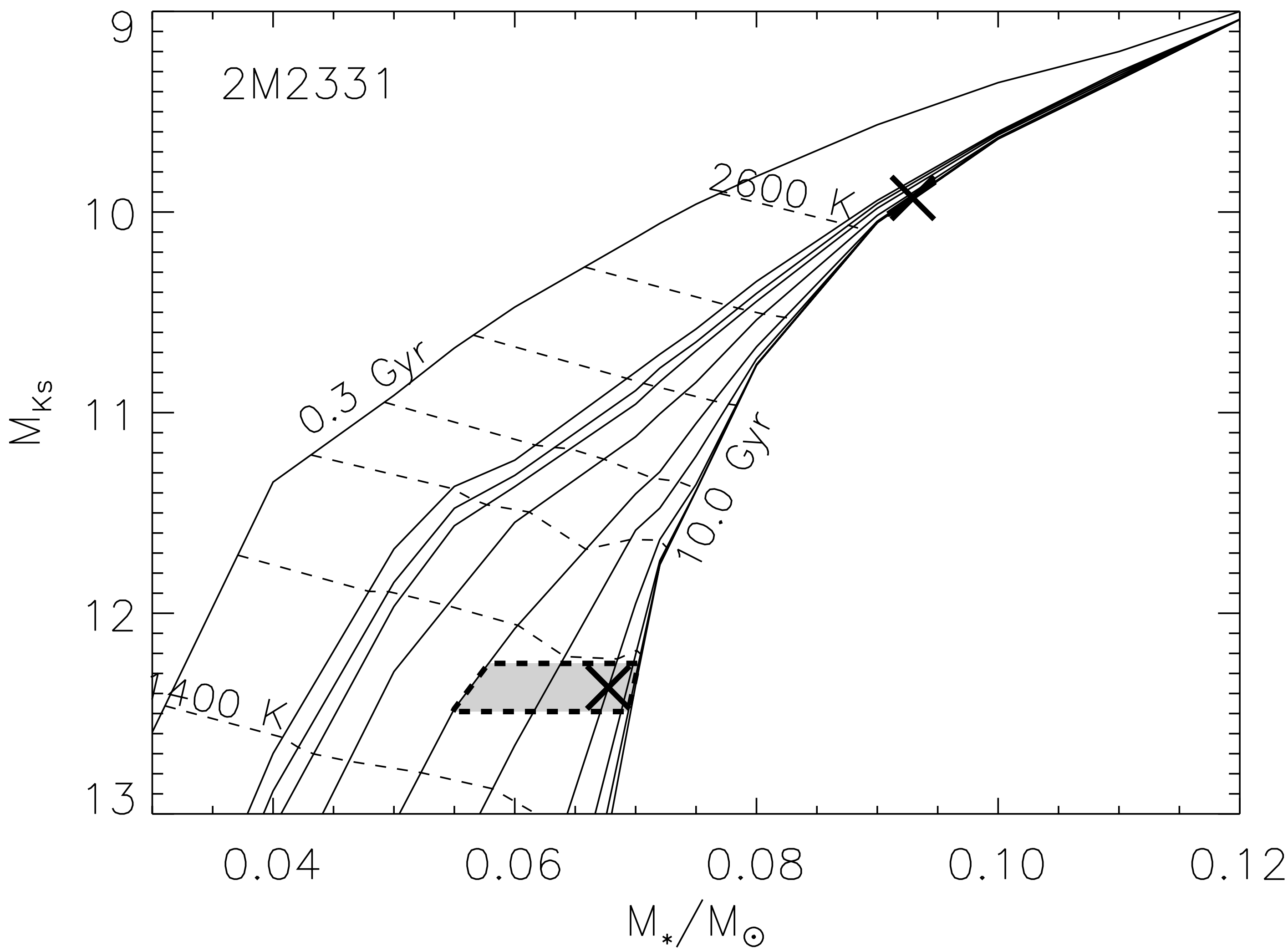

Fig. 11.— The same as for figure 3 except for 2M2331. This system is associated with the F8 star HD221356 (Gizis et al. 2000) which has a Hipparcos parallax of 26.2 ± 0.6 pc. The system is very wide with a separation of 0.057 pc between HD221356 and the 2M2331 system (Gizis et al. 2000). The models suggest a mass for 2M2331A of 0.093 $M_{\odot}$ with a range $0.091 - 0.095 M_{\odot}$ with temperatures of 2670 K (2640-2700K). For 2M2331B the models suggest a mass of $0.067 M_{\odot}$ with a range $0.055 - 0.070 M_{\odot}$ with temperatures of 1560K (1470-1584 K), making 2M2331B a definite brown dwarf companion.

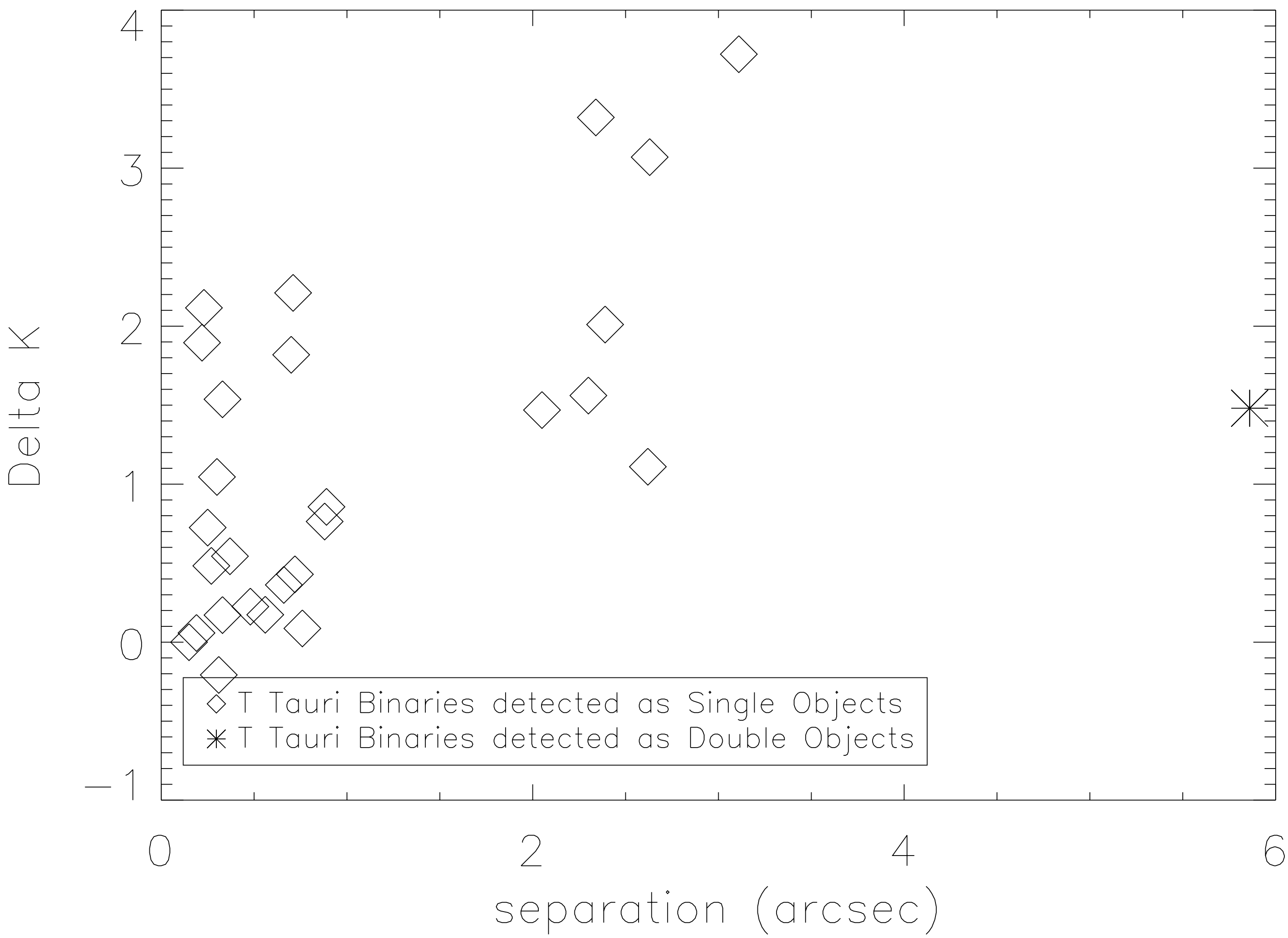

FIG. 12.— It is possible that the reason none of these 2MASS based surveys have detected wide low mass binaries is because the 2MASS pipeline flags blended binaries as "extended" and they are left out of the point source catalog completely. To check the validity of this possibility we plot above all the T Tauri binaries from White & Ghez (2001) found in the 2MASS second release point source catalog. None of these binaries were classified as extended sources sources, hence they each had at least one entry in the 2MASS point source catalog. However, the low angular resolution of 2MASS resulted in only systems with separations greater than $\sim 4''$ actually being classified as binaries. All systems tighter than $3''$ were unresolved and classified as single stars. A fainter sample of white dwarf binaries yielded the same result. We found no examples of binaries tighter than $2''$ being removed from the point source catalog. Therefore, we feel the lack of detection of wide low mass systems is not a selection effect from the initial use of the 2MASS point source catalog to define candidate low mass systems by Gizis et al. (2000); Kirkpatrick et al. (2000); Burgasser et al. (2003); Cruz et al. (2003).

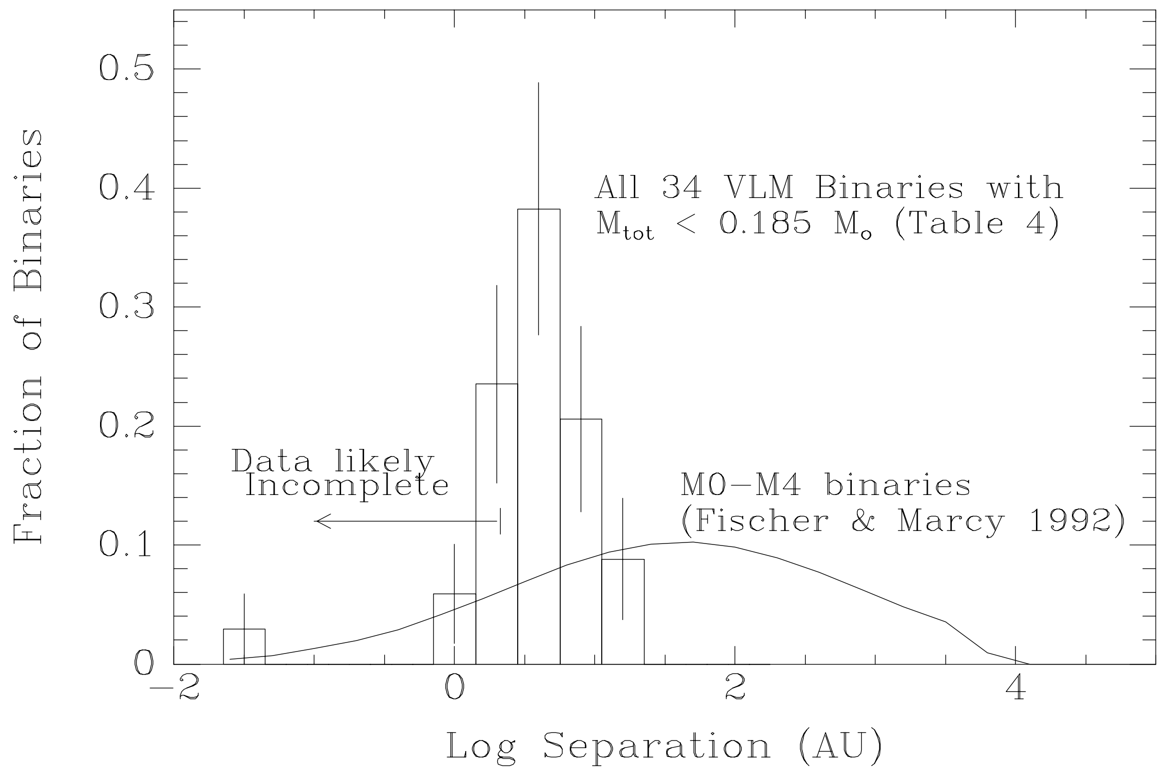

Fig. 13.— Here we plot all 34 VLM binaries from Table 4. Note how VLM binaries appear to have smaller separations compared to the M0-M4 binaries of Fischer & Marcy (1992). Both distributions are normalized to unity binary fraction. We have not tried to correct for instrumental incompleteness. Hence we underestimate the number of VLM binaries with $a < 2$ AU. Poisson error bars are plotted; the sharp peak at 4 AU and the lack of any wide ($a > 16AU$) systems are real features of the distribution and are significantly different from that observed in more massive M0-M4 binaries ($M_{tot} \gtrsim 0.3M_{\odot}$). Binary systems with $M_{tot} < 0.185M_{\odot}$ appear ~ 10 times tighter compared to just slightly ($2-5$ times) more massive M0-M4 binaries. We have converted the semi-major axis distribution values of Fischer & Marcy (1992) to observed separation by dividing the semi-major axis values by 1.26 (see equation 7 in Fischer & Marcy (1992)).

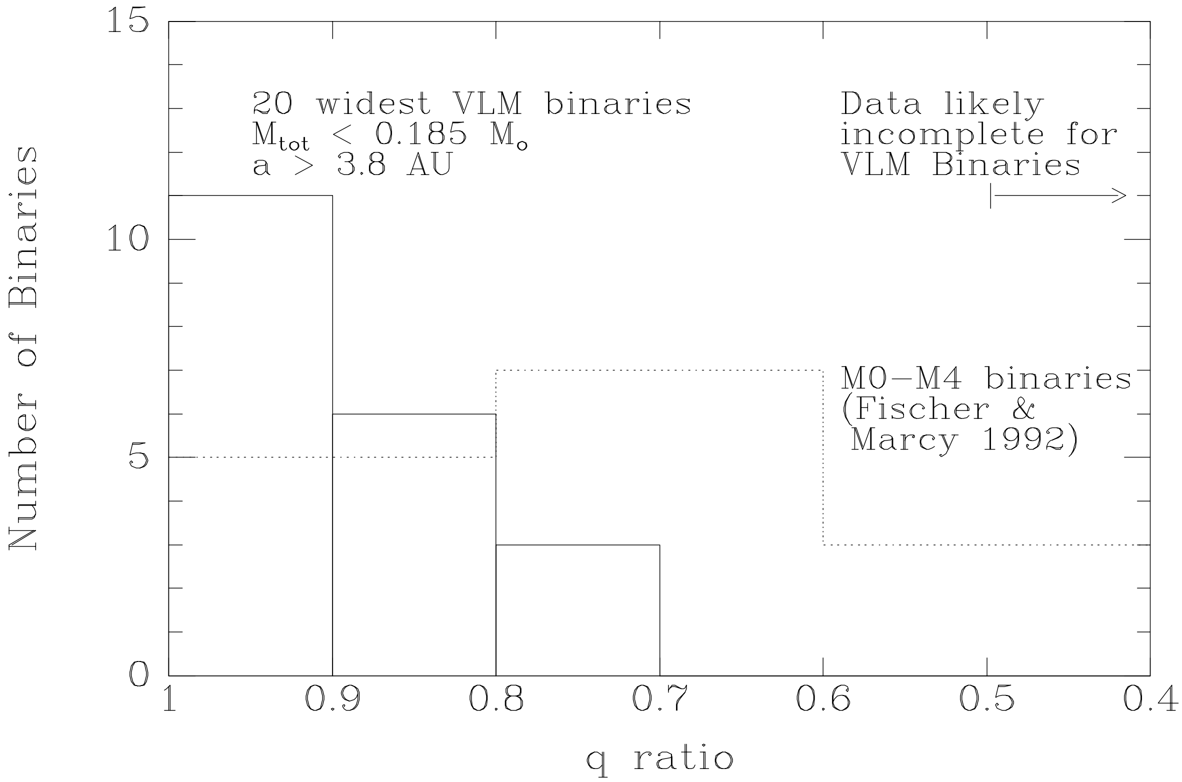

FIG. 14.— Here we plot the 20 widest ($a > 3.8$ AU) VLM binaries from Table 4. We see that VLM binaries appear to have a q mass ratio peaked near unity. This is quite different from the much flatter distribution of M0-M4 binaries (dotted line) of Fischer & Marcy (1992). The difference is likely real, and not a insensitivity effect, since the high-resolution AO and HST observations should be sensitive to mass ratios as low as $q \sim 0.5$ if $a \gtrsim 3.8$ AU (Bouy et al. 2003; Burgasser et al. 2003). However, for very faint companions both HST/WFPC2 and AO surveys are likely incomplete for tight ($a \lesssim 8$ AU) VLM binaries with $q \lesssim 0.5$. Therefore, no conclusions can currently be drawn about the likelihood of VLM systems with $q < 0.5$ since we are largely insensitive to such systems in the current studies.

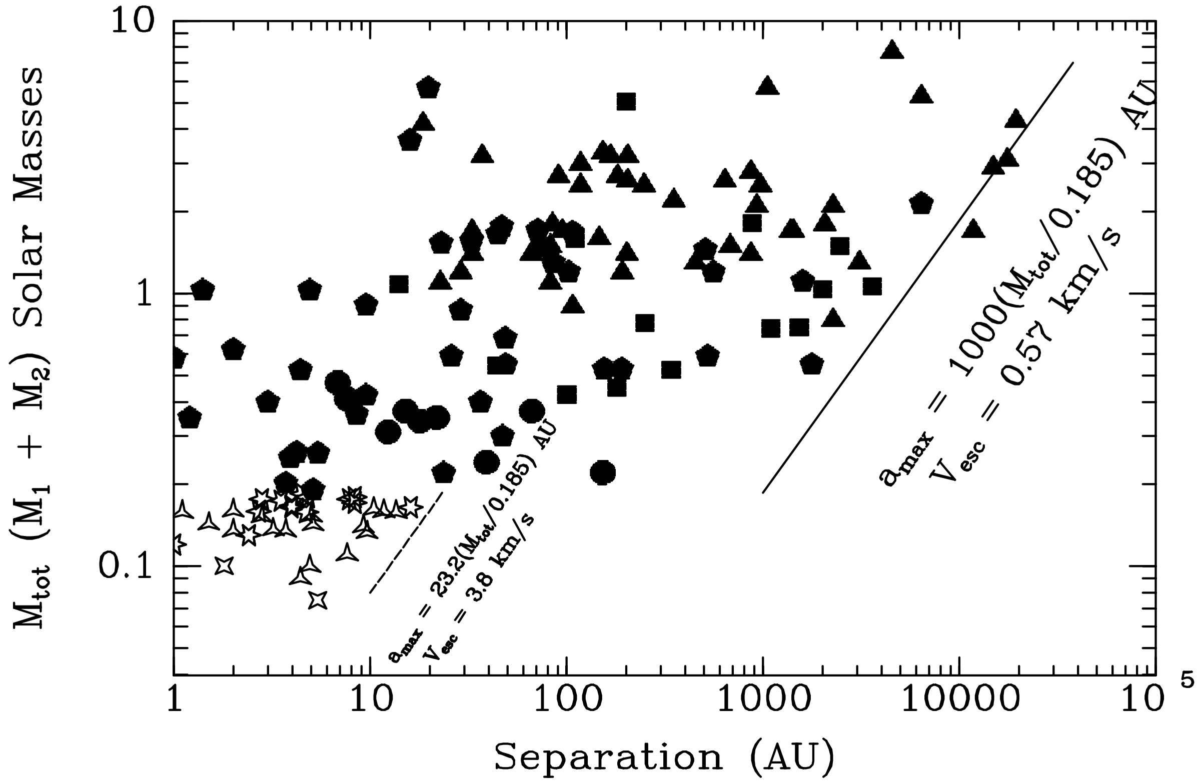

Fig. 15.— Here we plot all 34 currently known VLM binaries. The nine M8.0-L0.5 systems of this paper plus seven more VLM M binaries from Table 4 are plotted as open six sided stars. The L dwarf binaries of Koerner et al. (1999); Martín, Brandner, & Basri (1999); Reid et al. (2001a); Bouy et al. (2003) are shown as open triangles, and the two T dwarf binaries of Burgasser et al. (2003) as open four-sided stars. For comparison, we have plotted all the visual M0-A0 binaries inside 25pc from Close et al. (1990) as solid triangles. In addition, low mass Hyades binaries from Reid & Gizis (1997b) are plotted as solid circles, low mass field M-dwarfs from Reid & Gizis (1997a) are plotted as solid pentagons. All A0-M5 star/brown dwarf systems are plotted as solid squares (Reid et al. 2001a). Note how there are no low mass systems with separations $> 16AU$. It is seen that for more massive binaries ($M_{tot} > 0.185 M_{\odot}$) the maximum observed separation can be fit to $a_{max} = 1000(M_{tot}/0.185M_{\odot})$ AU (solid line). When $a = a_{max}$ the escape velocity is $V_{esc} = 0.57$ km/s. However, for VLM binaries (where $M_{tot} < 0.185M_{\odot}$) the best fit of the widest systems is $a_{max_{VLM}} = 23.2(M_{tot}/0.185M_{\odot})$ AU (dashed line). For VLM systems with $a = a_{max_{VLM}}$ the escape velocity is 3.8 km/s. *Hence VLM binaries appear sharply tighter (a < 16 AU) and have escape velocities at least 3 km/s higher than more massive wide binaries.*

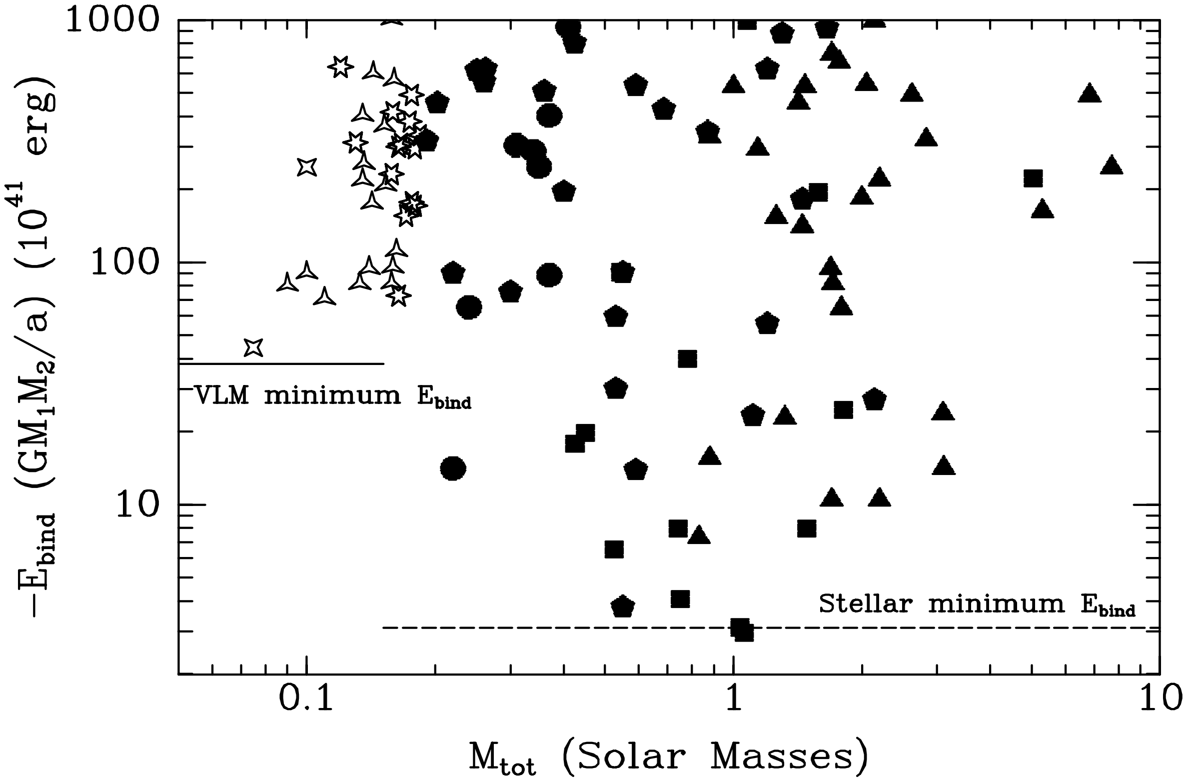

Fig. 16.— To see if low mass binaries really are more bound (i.e. "harder") we plot here the binding energy for all the systems in Figure 15. The data (individual masses and separations) are from Table 4 and the symbols are the same as in Figure 15. We see that the widest VLM binaries (open symbols) are ~ 16 times harder than their more massive wide binary counterparts (solid symbols). This effect was also noted by Burgasser et al. (2002).

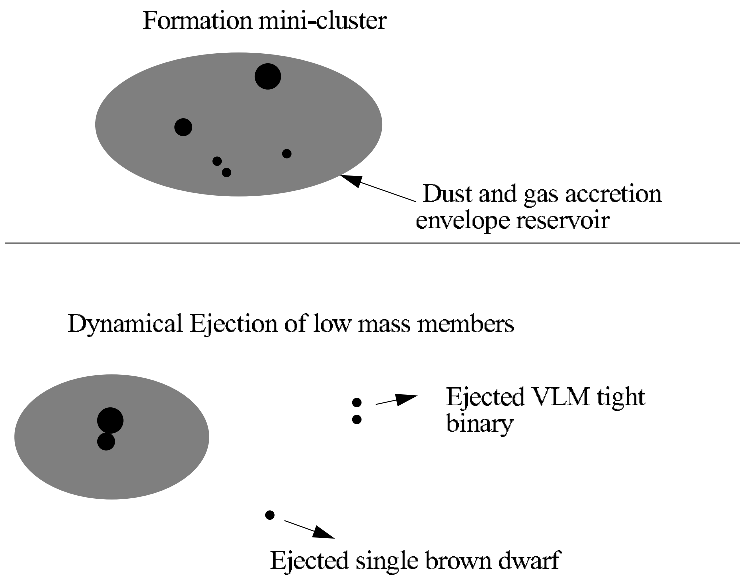

FIG. 17.— A simple cartoon of the hypothesized ejection of the low mass members of a formation mini-cluster. Typically a dissolving mini-cluster will evolve to a final hardened binary containing the most massive stars in the cluster. The other lower mass members are ejected through close encounters with the more massive members. If it is possible to eject VLM binaries, only tightly bound VLM binaries could survive the ejection process (Reipurth & Clarke 2001).